Status of QCD, Charm and Bottom Physics at CDF

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On behalf of the CDF Collaboration

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In this talk…

A lot of analyses are in progress at CDF, here not at all exhaustive summary!

I will show mostly new results…

- QCD/Jets Physics Today's Topics:
  - Inclusive jet cross-section
  - Underlying event studies
  - W + n jets
  - Diphoton events
  - γ + b/c cross-sections

- Not included:
  - Diffractive Physics
  - Exclusive Diffractive production: $\chi_c \rightarrow J/\psi + \gamma$
  - Jet algorithms
  - …

- B/C Physics Today's Topics:
  - B lifetimes in exclusive channels
  - $B_s \rightarrow \mu\,\mu$ search
  - Semileptonic B decays
  - CP asymmetries in D^0 decays
  - Baryons and Pentaquark searches

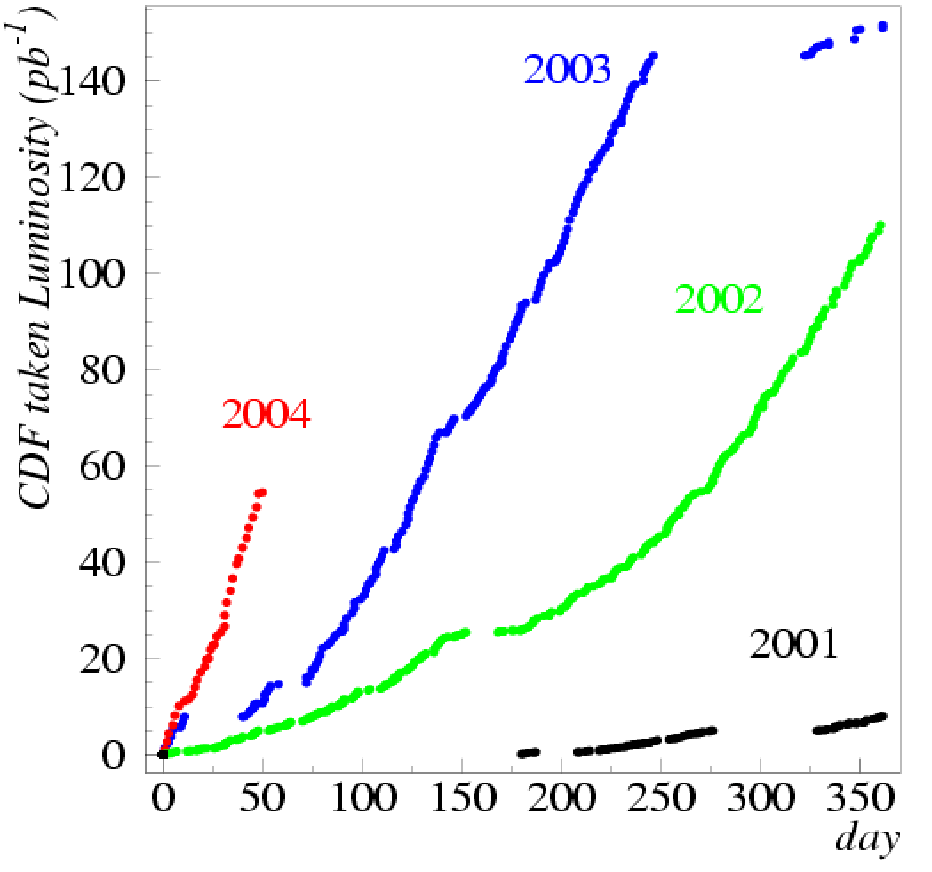
- Not included:
  - B, C, J/ψ cross-sections
  - B Hadron masses
  - Two body charmless decays
  - Tagging studies
  - $X(3872) \rightarrow J/\psi\,\pi\,\pi$ state
  - Branching ratio measurements
  - …

Tevatron performance

• As you know the Tevatron is working very well this year

• Record Initial luminosity = 7.2 X 10^{31} sec^{-1} cm^{-2}

• Detector efficiency ~85-90%



~300 pb^{-1} on tape

~100-200 pb^{-1} used for analysis so far

QCD and Jet Physics

Motivation

- Tevatron = Jet factory
- All production processes are "QCD related":

Optimal understanding is basic for all analyses

  - Main parameters (ex.: gluon PDFs in high x)
  - Non-perturbative regime (ex.: underlying event studies)
  - Studies of specific processes where QCD is important (ex.: diphotons, W+jets, γ+b/c)

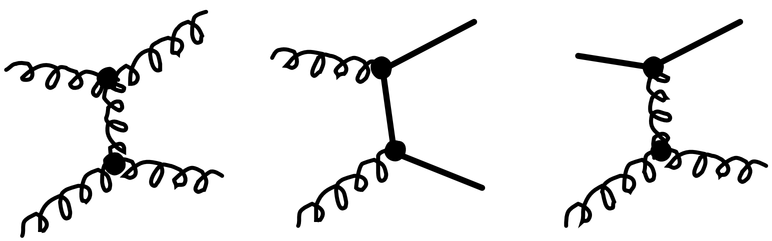
- Probe higher energy scales:
  - Higher $\sqrt{s}$ ➔ higher s (factor 5 for E_T > 600 GeV w.r.t. run I)
  - Precise test of perturbative QCD at NLO
  - Look for deviations ➔ new physics
- Other studies of interest:

Diffraction, hadron spectrocopy…

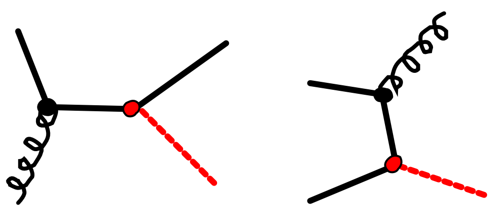
Inclusive Jet Cross Section

- **Very challenging analysis:**
  - **Theoretical computation is difficult (NNLO still going on…)**
  - **Uncertainties in PDFs**
  - **Cross-section varies with E_t by 8 orders of magnitude (precise energy scale)**

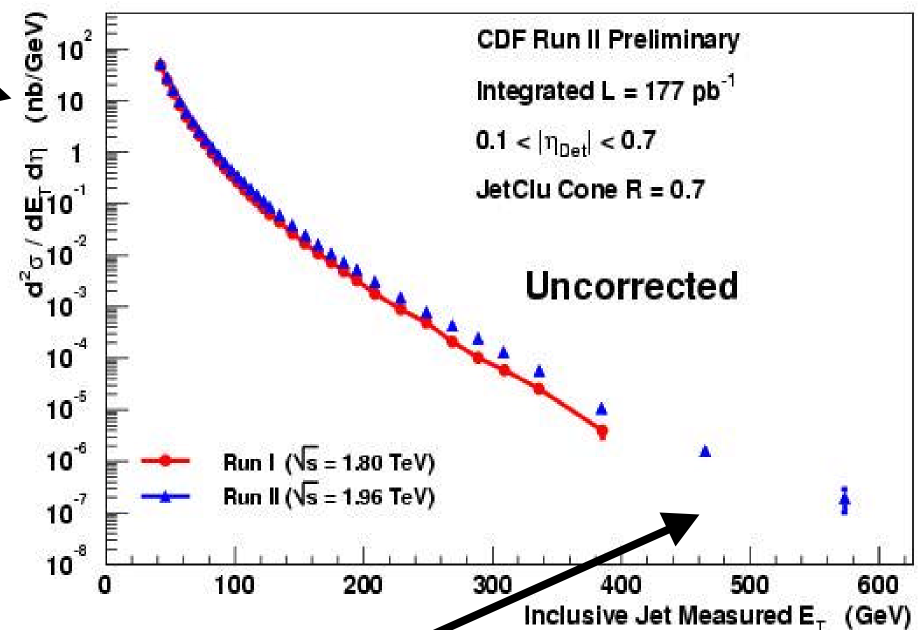
Run I vs Run II data



Leading diagrams for dijet events



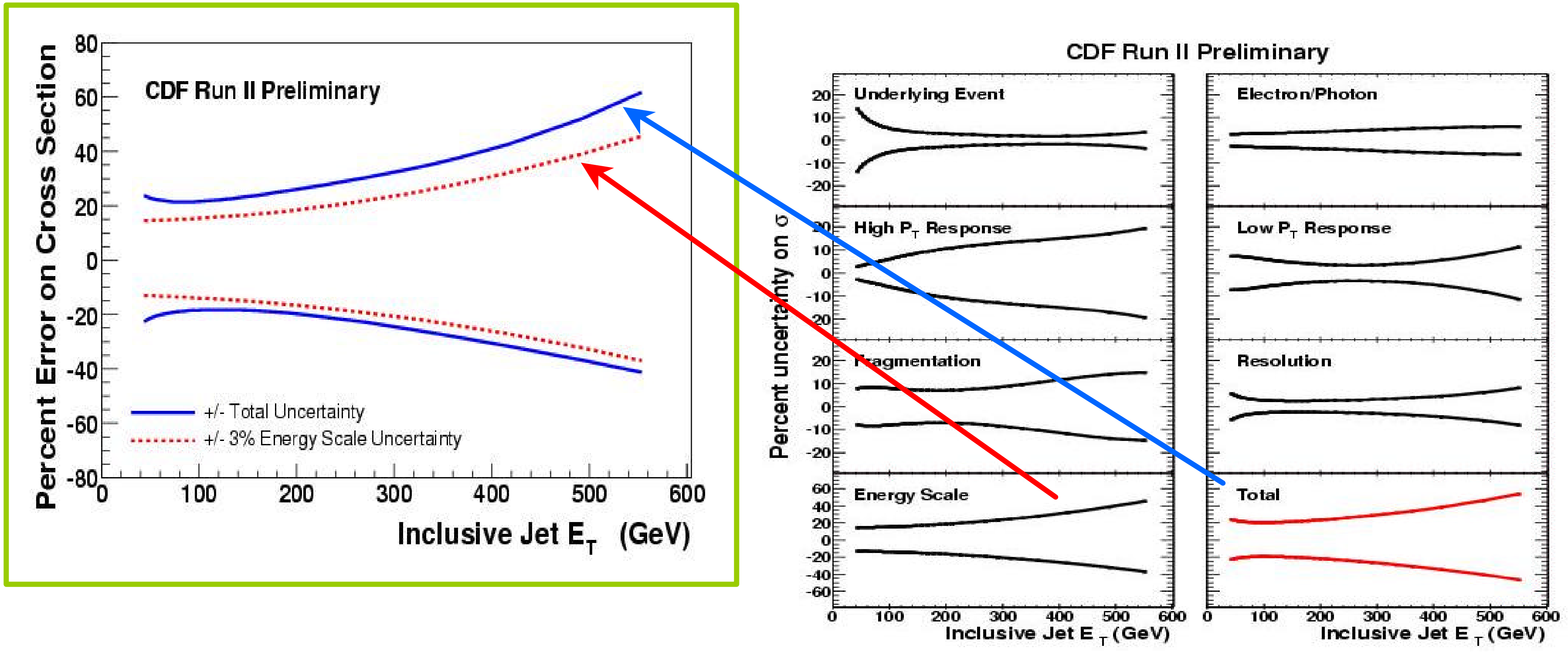
Leading diagrams for g-jet events



Jets with very high E_t in Run II

Inclusive Jet Cross Section

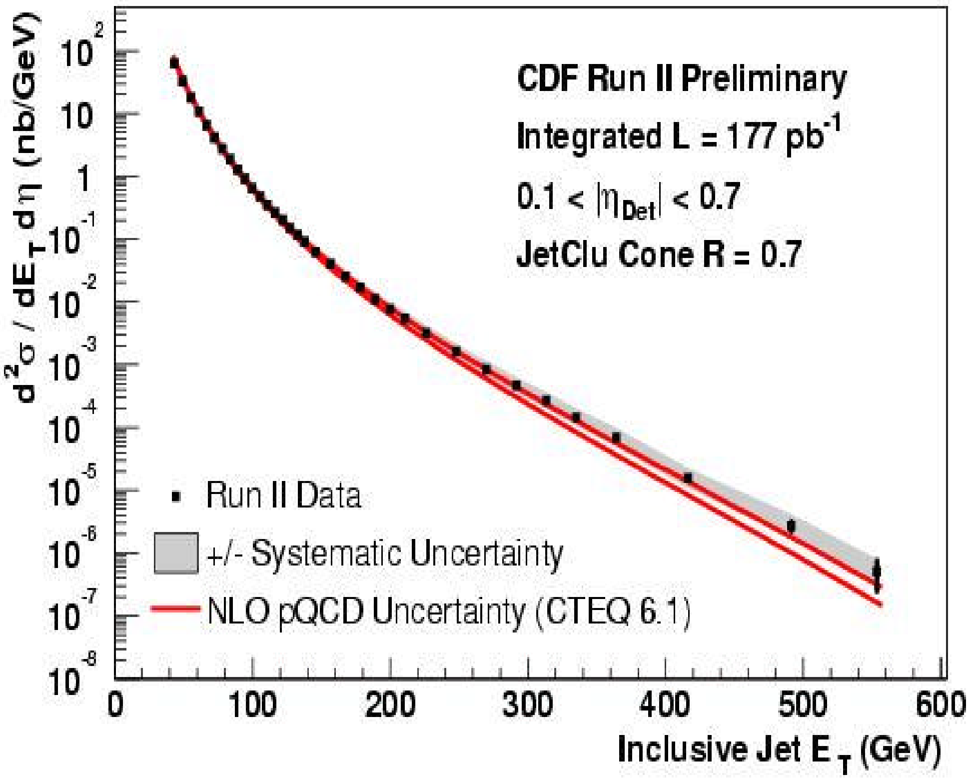
- **Theoretical error dominated by PDFs**
- **Experimental error dominated by energy scale**

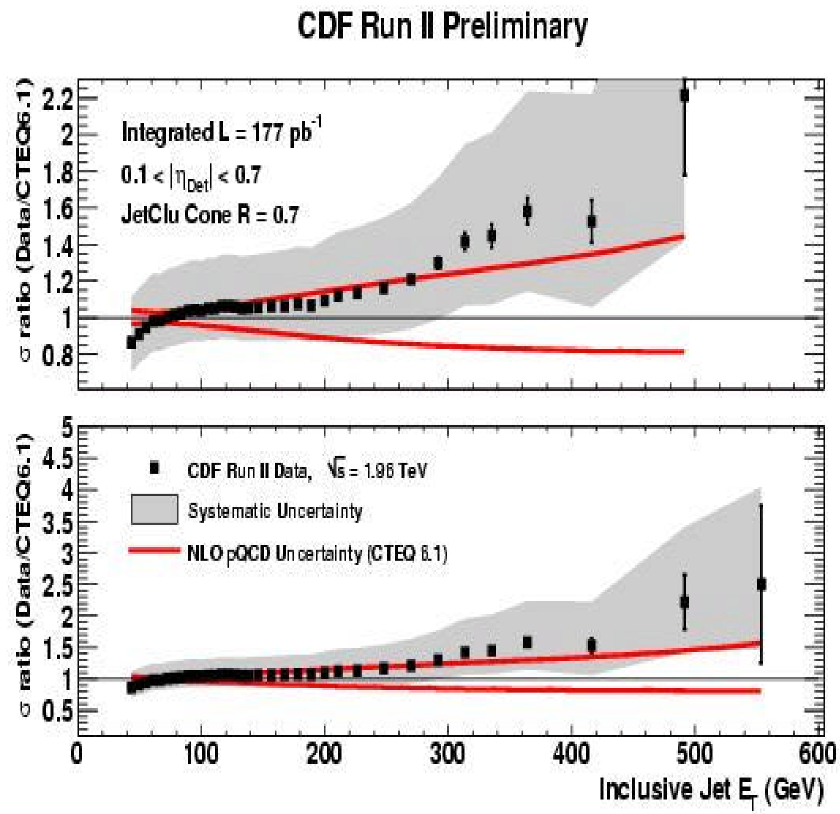


Better understanding of the calorimeter response → reduce the systematic uncertainty

Inclusive Jet Cross Section

- **There was an apparent excess in Run I data**
- **SM explanation: gluon PDF was not well constrained at high x**



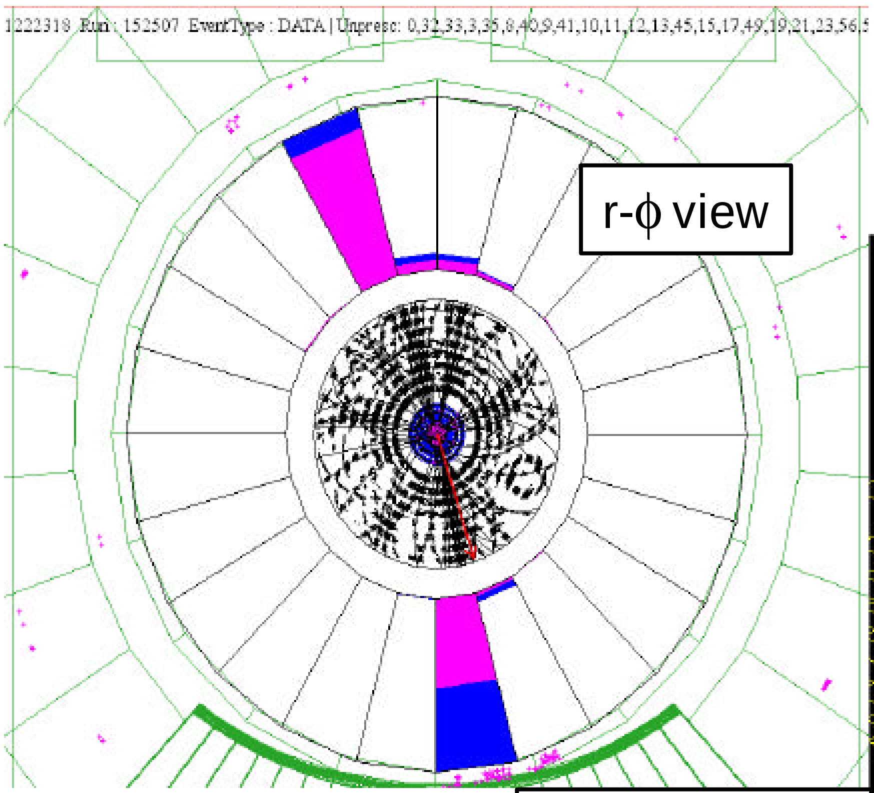


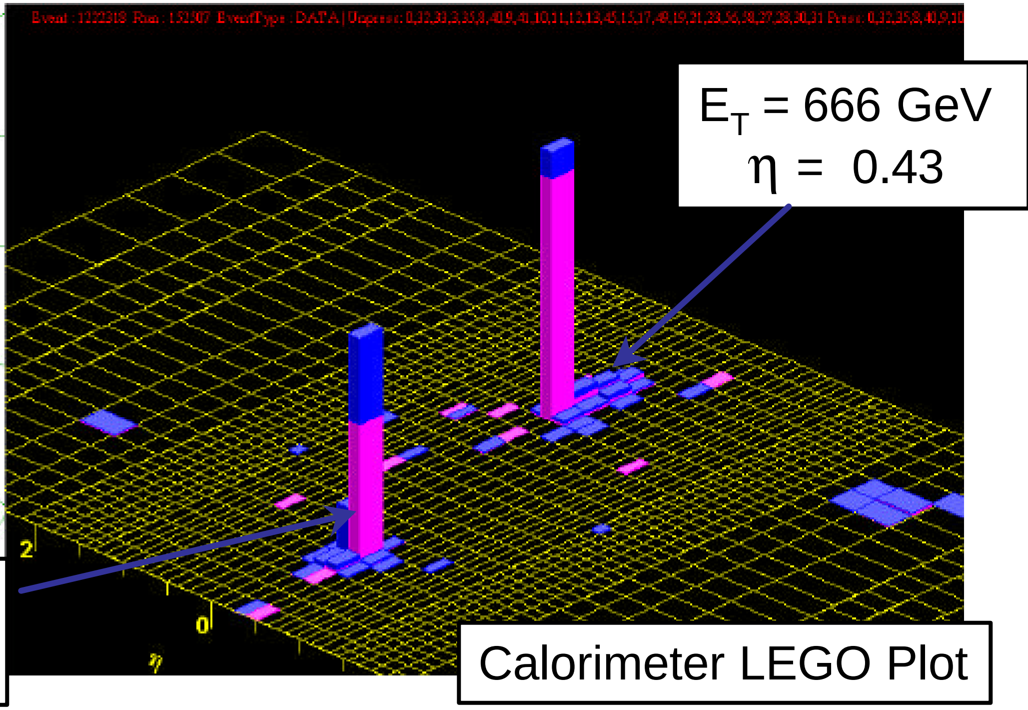
Data currently agrees with NLO prediction within errors

High E_T Jets

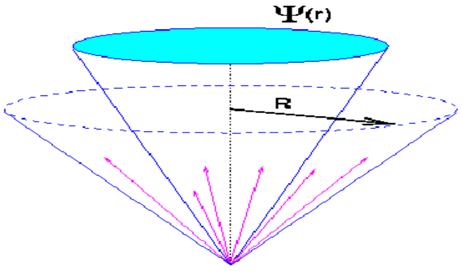
- Starting an era of QCD precision measurements at Hadron Colliders
- Studying "QCD backgrounds" in order to look for new Physics

Highest mass di-jet event so far (Mass = 1364 GeV/c^2)





Energy flow inside jets



$$\Psi(r) = \frac{1}{N_{\rm jets}} \Sigma_{\rm jets} \frac{E_T(0,r)}{E_T^{\rm jet}(0,R)}$$

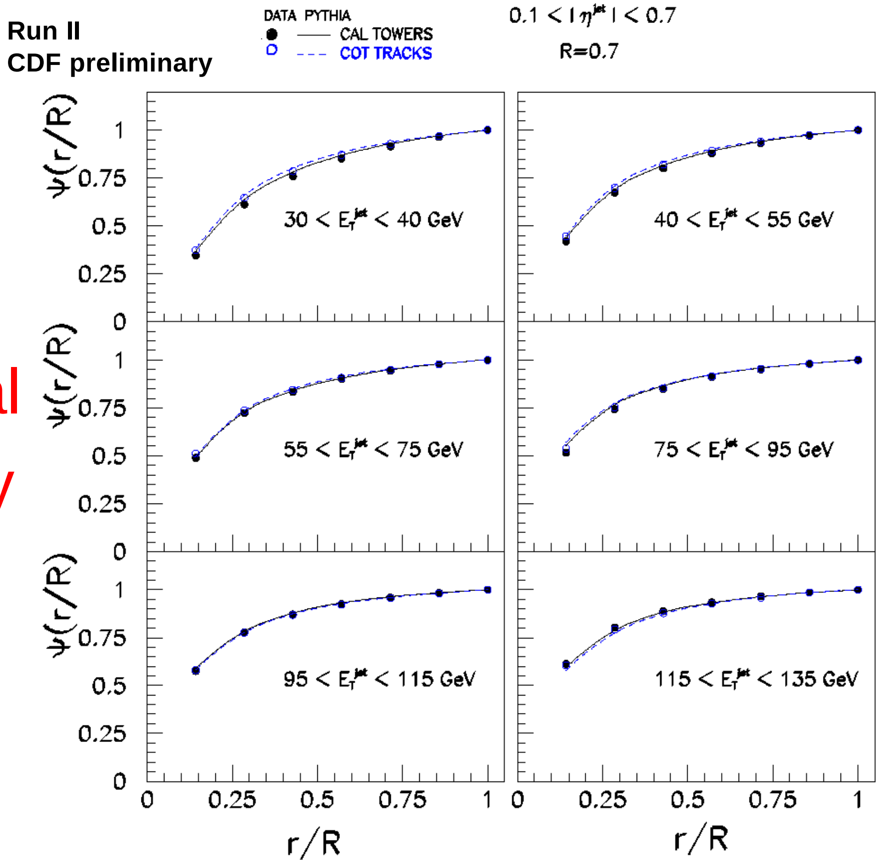
- Jet shape:

fractional energy flow

$\Psi(r) = E_T(0:r) / E_T(0:R)$,

where R=1

- In central region, do it with
  - Calorimeter towers (?)
  - Charged tracks (?)
- Shapes are nearly identical
- Pythia and data agree very well in the central region

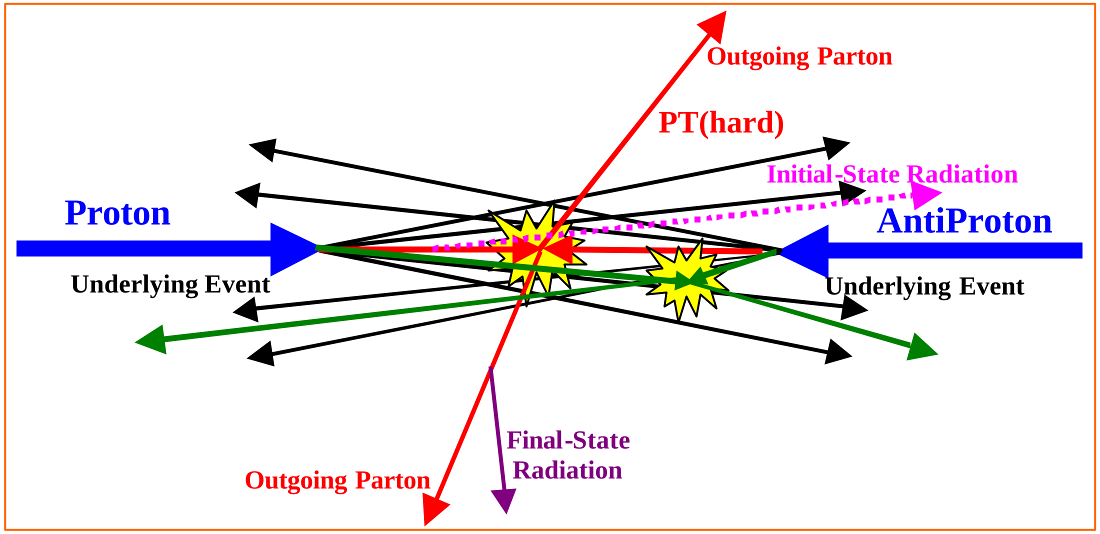


Underlying event studies

The Underlying Event is everything but the two outgoing Jets

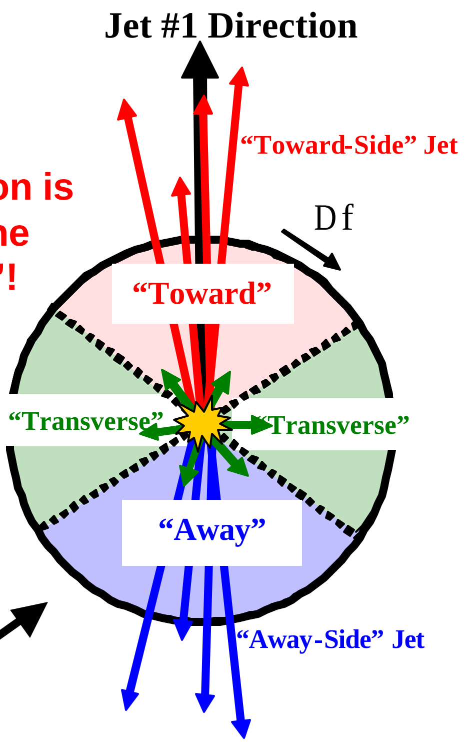
- **Whole event:**
  - **Hard scattered partons**
  - **Initial state radiation**
  - **Final state radiation**
  - **Multi-parton interactions**
  - **Proton remnants**
  - **… everything is mixed with color reconnections**

- **Underlying event: ~(whole event)-(hard scatt)**
  - **ISR**
  - **A fraction of FSR**
  - **Multi-parton interactions**
  - **Proton remnants**
  - **… but not completely independent from the hard scattering part**



Underlying event studies

- Underlying event pollutes many analyses
- Basic in order to understand the jet fragmentation



"Transverse" region is very sensitive to the "underlying event"!

- It must be tuned as well as possible
- Default Pythia does not describe well the CDF data → Pythia CDF tune A

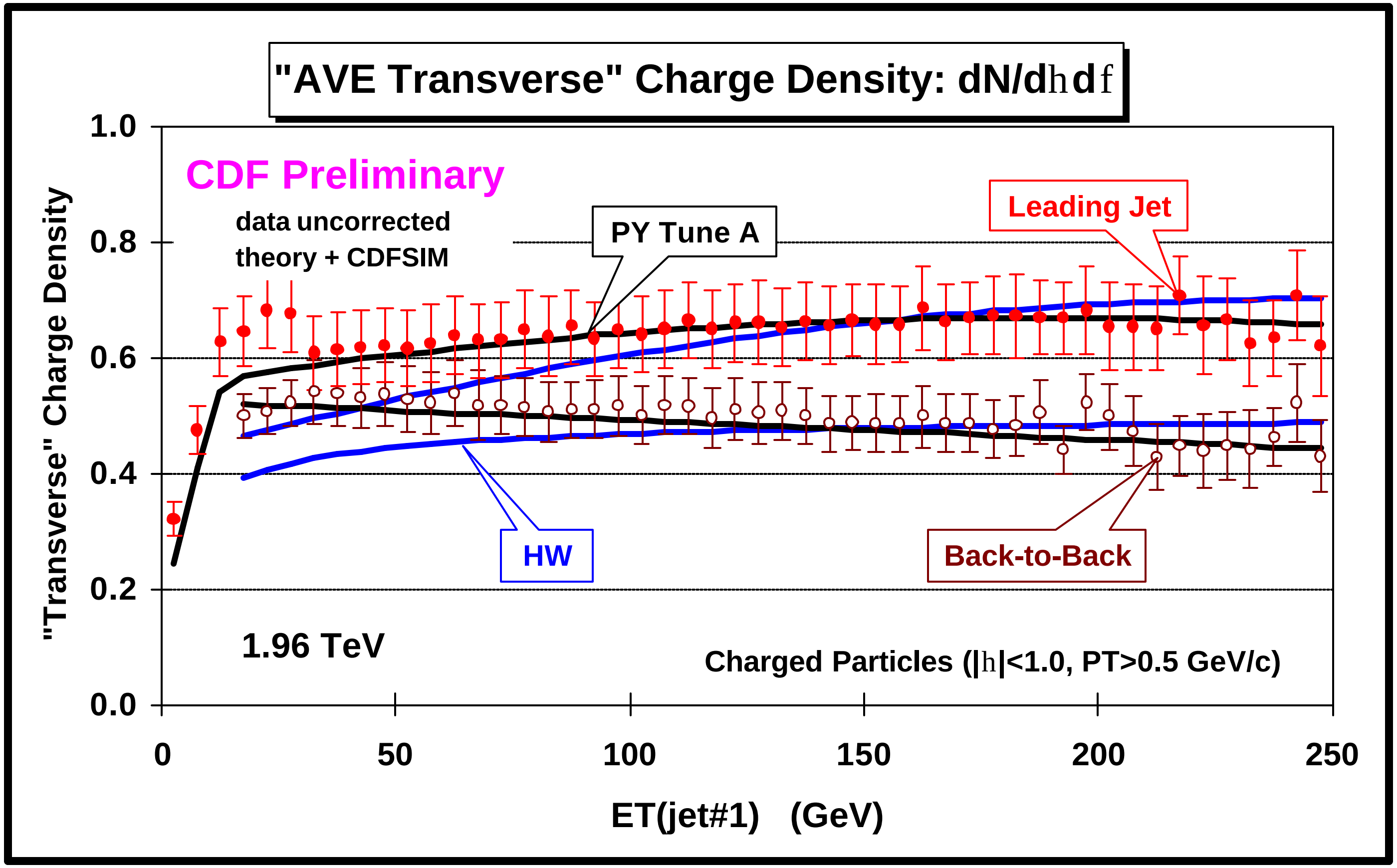
The method

The picture

- Look at charged particle correlations in the azimuthal angle $\Delta\phi$ relative to the leading calorimeter jet (JetClu R = 0.7, $|\eta| < 2$)
- Define $|\Delta\phi| < 60^o$ as "Toward", $60^o < |\Delta\phi| < 120^o$ as "Transverse", and $|\Delta\phi| > 120^o$ as "Away"
- All three regions have the same size in η-ϕ space, $\Delta\eta \times \Delta\phi = 2 \times 120^o = 4\pi/3$

Underlying event studies

- **PYTHIA tune A (on Run I data) reproduces well Run II data**
- **HERWIG works only at high E_{T1}**



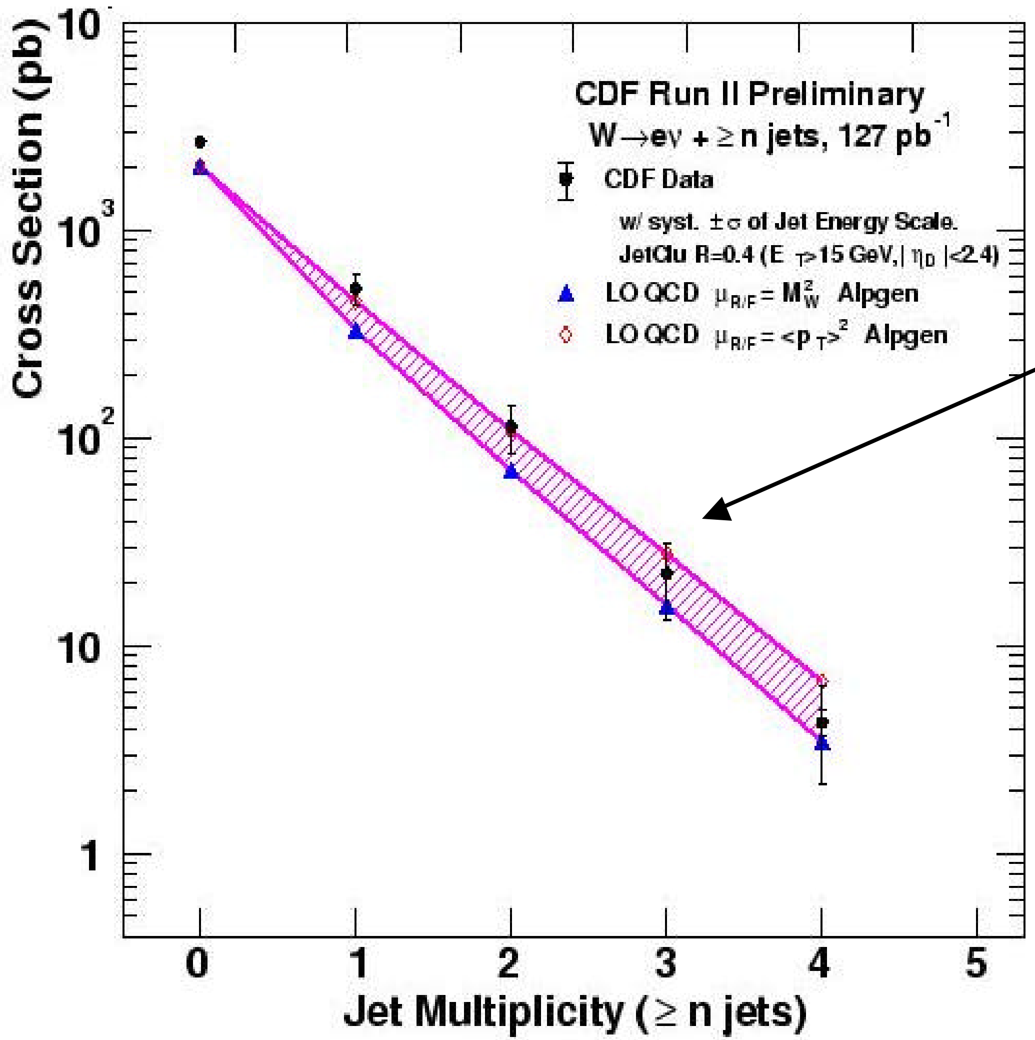
<u>Average charged particle density</u>, **dN/dηdϕ, in the “transverse” region versus E_T(jet#1) for “Leading Jet” and “Back-to-Back” events compared with PYTHIA Tune A and HERWIG**

The global comparison between data and QCD predictions is reasonable

We go to some specific channels now...

W → eν + jets cross section

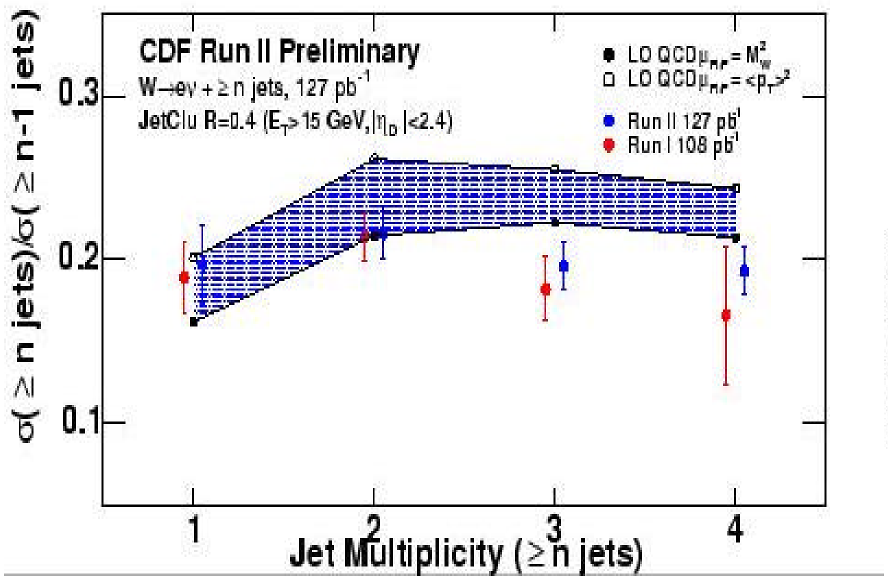
- **Test of QCD predictions at large Q^2, fundamental channel for Top/Higgs.** **Compared to LO ALPGEN + Herwig**
- **One energetic and isolated electron + high E_T jets**
- Backgrounds: Top dominates for 4-jet bin, QCD is an important fraction in all jet bins



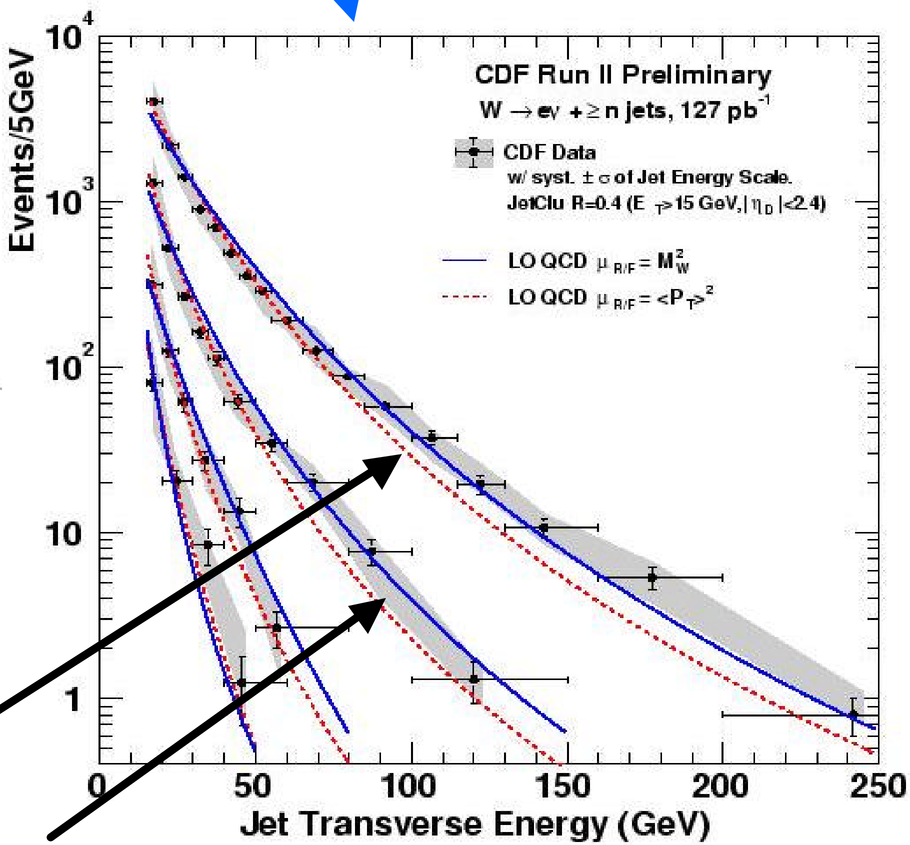
Results agree with LO QCD predictions within the errors!

Systematic uncertainty (10% in σ_1 to 40% in σ_4) limits the measurement sensitivity

W → eν + jets cross section



Differential cross section as a function of jet E_T



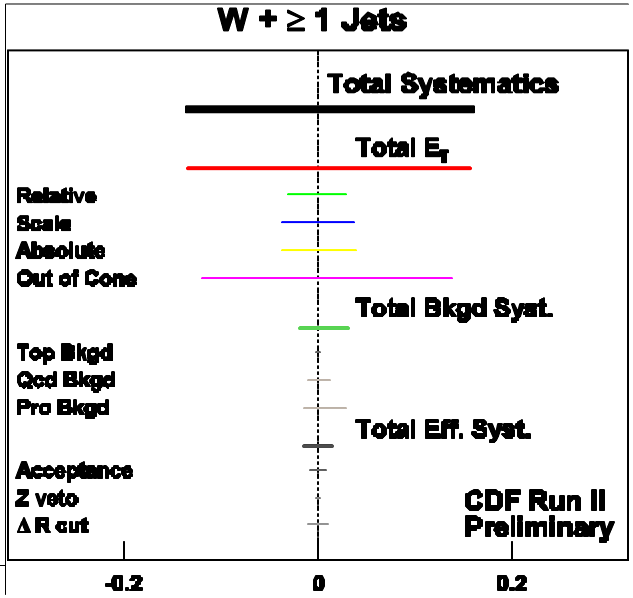
The ratio $\mathbf{R}_{n/(n-1)}$ measures the decrease in the cross section with the addition of one jet.
It depends on α_s

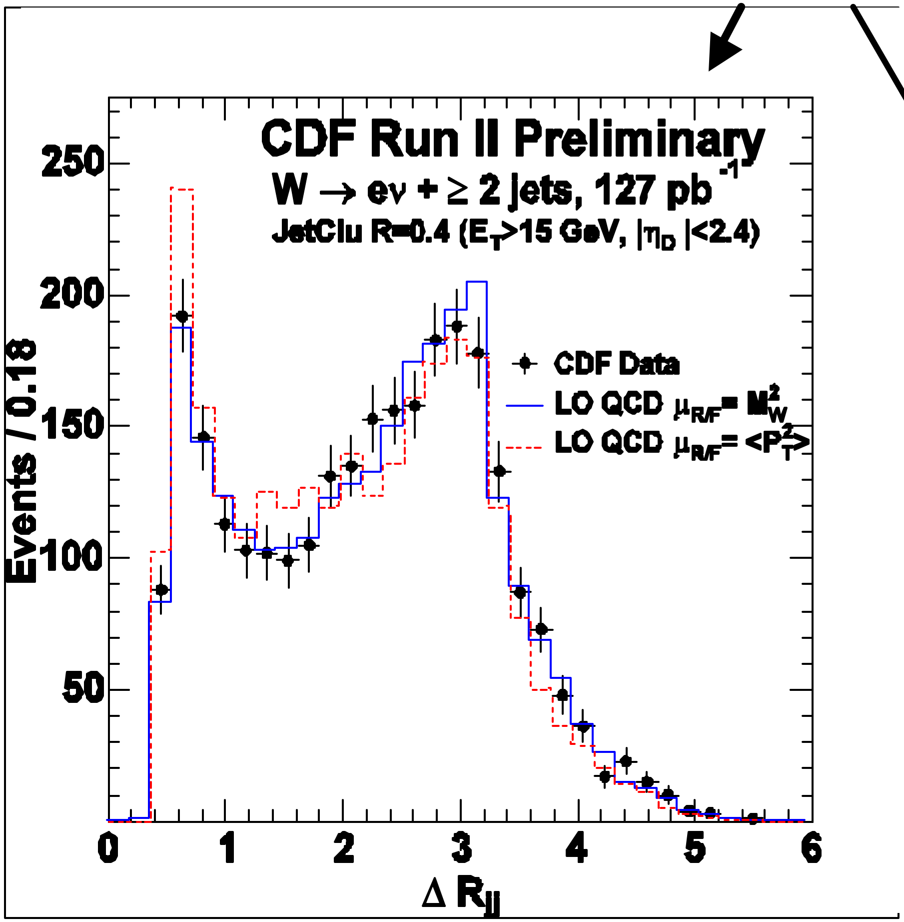
Highest ET jet in W+>=1 jet
Second highest ET jet in W+>=2 jet, etc…

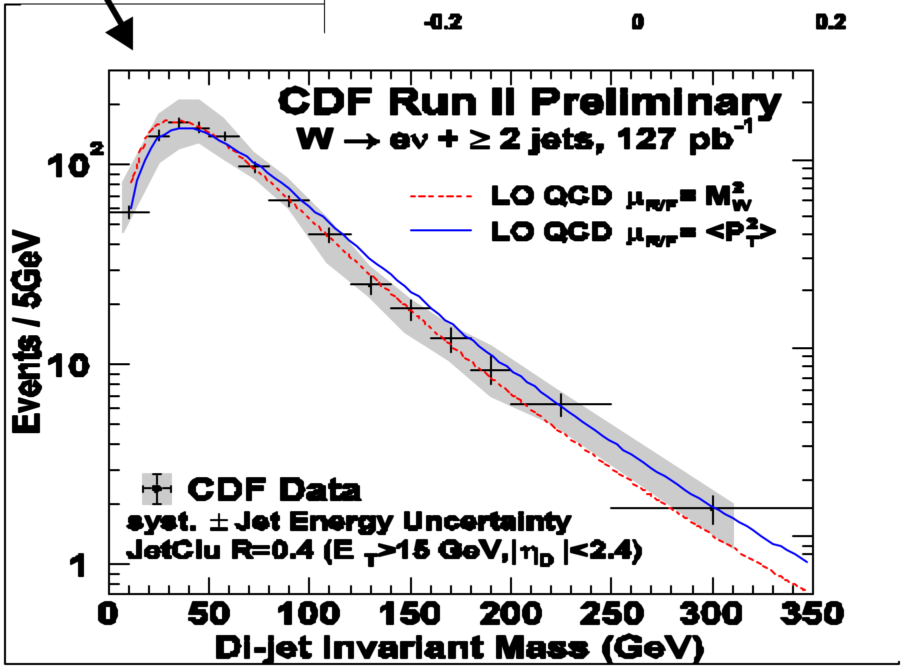
W → eν + jets cross section

- Energy "out of cone" dominates the systematic uncertainty

- Data and simulation agreement is reasonable





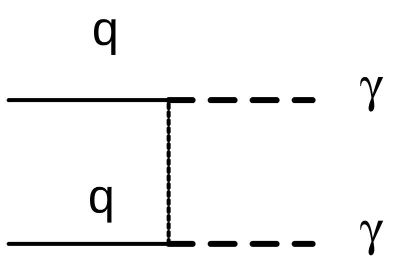


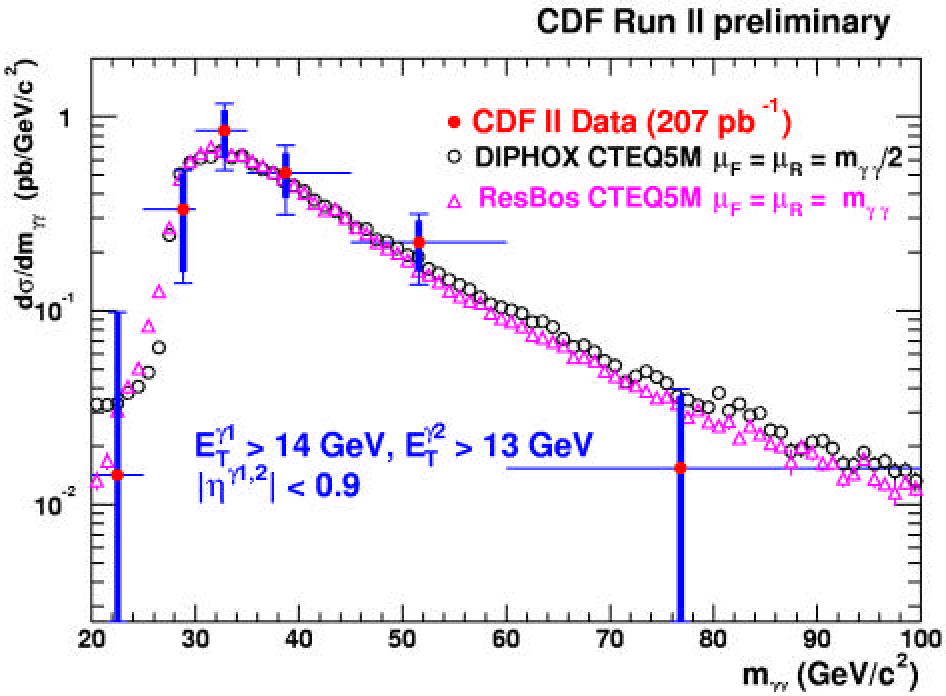
Diphoton cross-section measurement

- Study of diphoton QCD production
  - Two isolated and energetic high E_t photons in the central region

- Comparison with QCD predictions: DIPHOX and ResBos

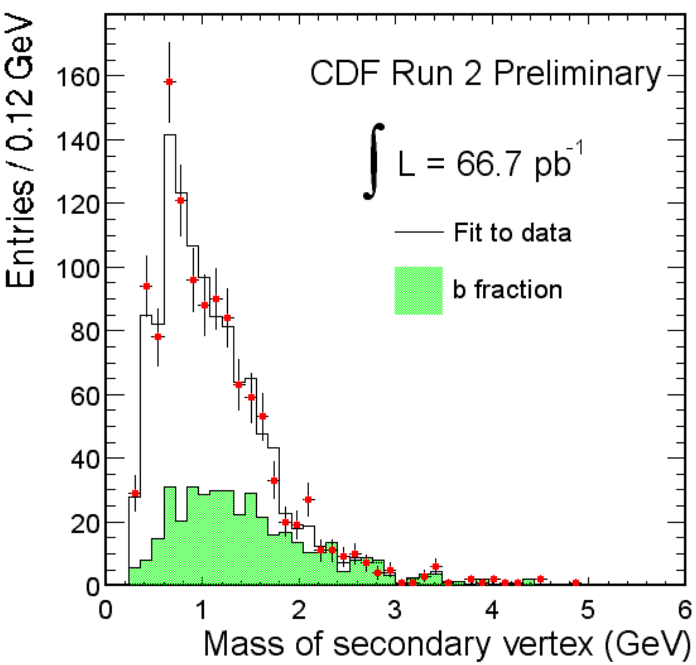
Good agreement between data and QCD predictions!

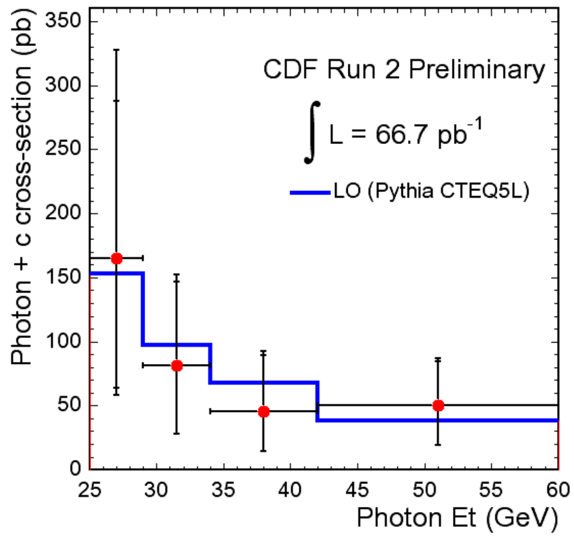


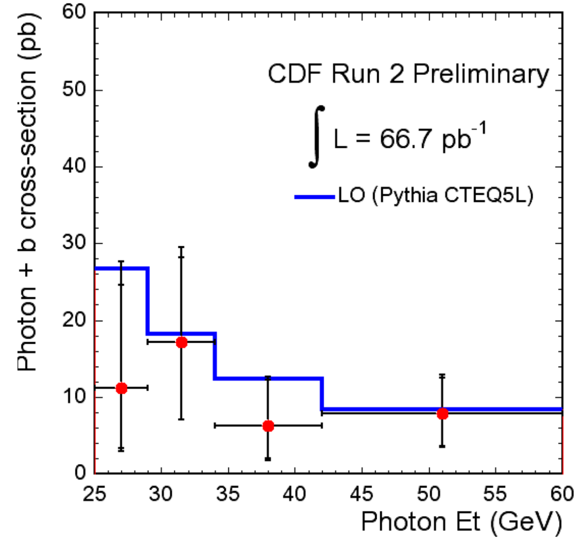


γ + b/c cross-section

- It probes the heavy flavor content of the proton, sensitive to new Physics
- Basic requirements:
  - One isolated and High E_t γ (> 25 GeV)
  - One jet with a secondary vertex (b/c "like" jet)
- Fit on the secondary vertex mass distribution of the tagged jets to determine the number of events containing b, c and uds quarks in the data







Cross-section measurements agree with the QCD predictions

Overall fit

σ(b + γ) = 40.6 +/- 19.5 (stat.) + 7.4 -7.8 (sys.) pb
σ(c + γ) = 486.2 +/- 152.9 (stat.) + 86.5 -90.9 (sys.) pb

QCD summary

- **Measured inclusive cross-section agrees with NLO QCD**

Trying to reduce the systematic uncertainties

- **Modeling the Underlying Event is important for precise Jet measurements**

A tuned PYTHIA version agrees well with CDF data

- **Diphoton analysis and g + heavy quark production**

Results are found to be consistent with Pythia LO predictions

No evidence so far of new physics production

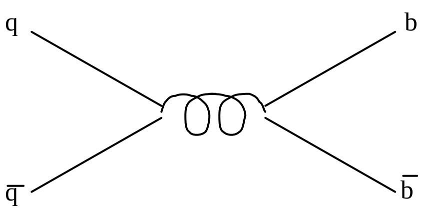
- **Study of W+jets is important to test QCD predictions at large Q^2**

It is a very important channel for Top/Higgs Physics

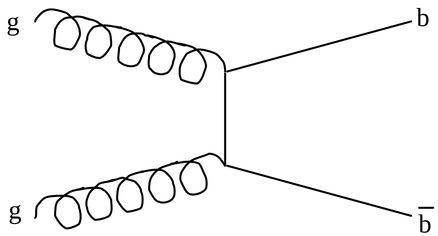
Charm and Bottom Physics

B Physics at CDF

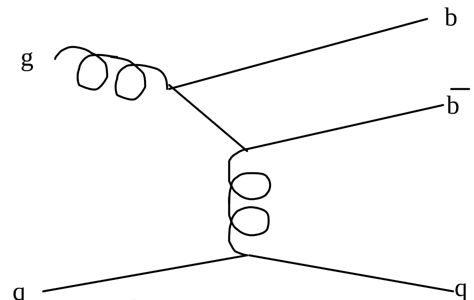
BB production mechanics in hadron collider:



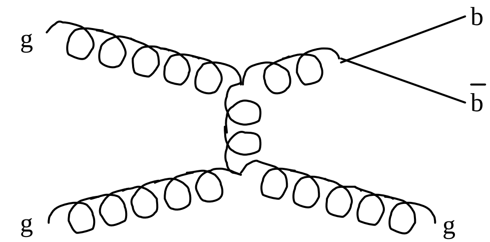
Flavor Creation (annihilation)



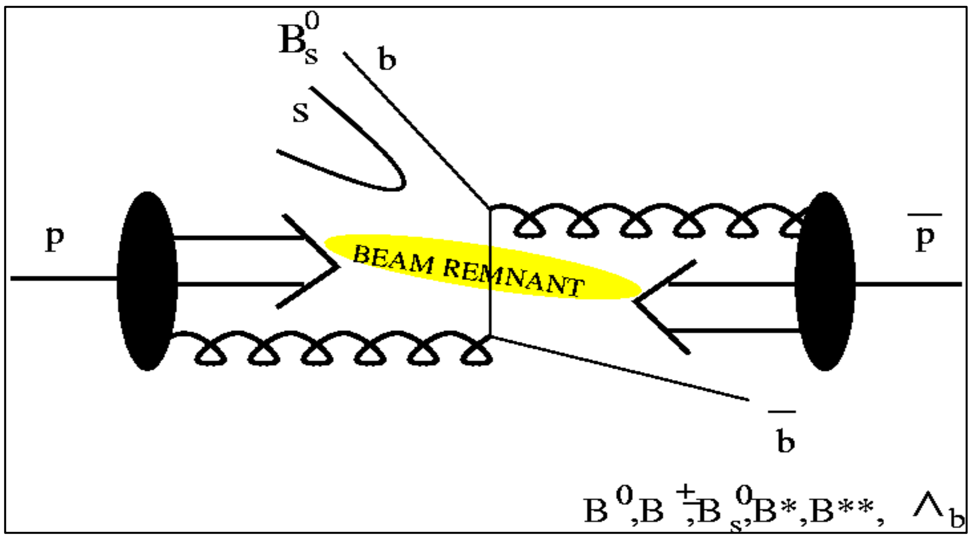
Flavor Creation (gluon fusion)



Flavor Excitation



Gluon Splitting



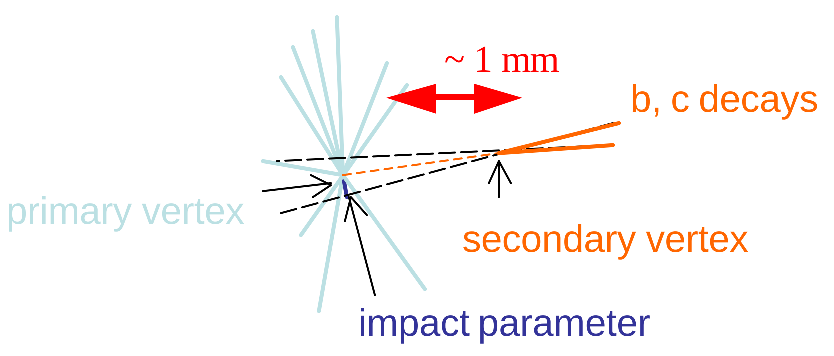
- Huge cross-section (~100 µb)
- All *B* species produced:
  - –B_u,B_d,$\mathbf{B_s}$,$\mathbf{B_c}$,L_b,…

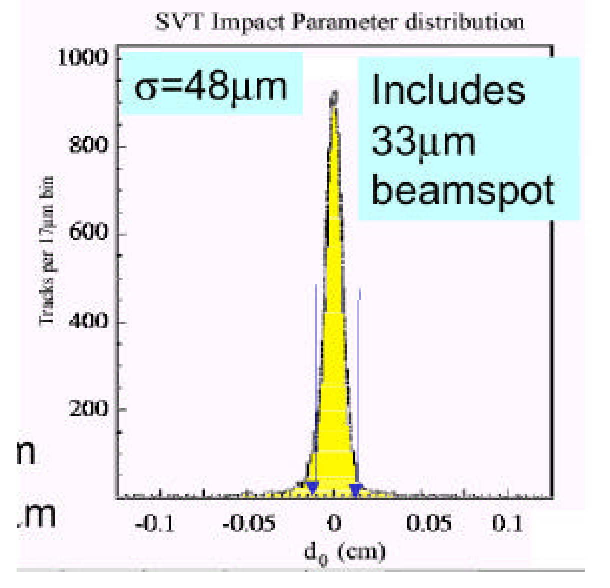
BUT s (bb) << s (pp) Þ B events have to be selected with specific triggers…

Trigger requirements: large bandwidth, background suppression, deadtimeless

B Triggers at CDF Run II

- Di-lepton - dilepton sample
  - $p_T(\mu/e) > 1.5/4.0$ GeV/c
  - J/ψ modes, masses, lifetime, x-section
  - Yield 2x Run I (low Pt threshold, increased acceptance)
- lepton + displaced track - semileptonic sample
  - $p_T(e/\mu) > 4$ GeV/c, 120 μm < d0(Trk) < 1mm, pT(Trk) > 2 GeV/c
  - Semileptonic decays, Lifetimes, flavor tagging
  - B Yields 3x Run I
- Two displaced vertex tracks - hadronic sample
  - p_T(Trk) >2 GeV/c, 120 μm < d0(Trk) < 1mm, $\Sigma p_T > 5.5$ GeV/c
  - Branching ratios, B_s mixing…





B/C analyses in this talk vs. Trigger

- **Dilepton Trigger:**
  - **B hadron lifetimes with exclusive modes**
  - **$B_{s(d)}$ $\rightarrow$** mm **search**
- **Lepton + Displaced Track Trigger:**
  - **Yields in Semileptonic B decays**
- **Two Displaced Tracks Trigger:**
  - **CP Asymmetries and Decay Rate ratios in D^0 decays**
  - **Search for Pentaquarks**

B hadron Lifetimes

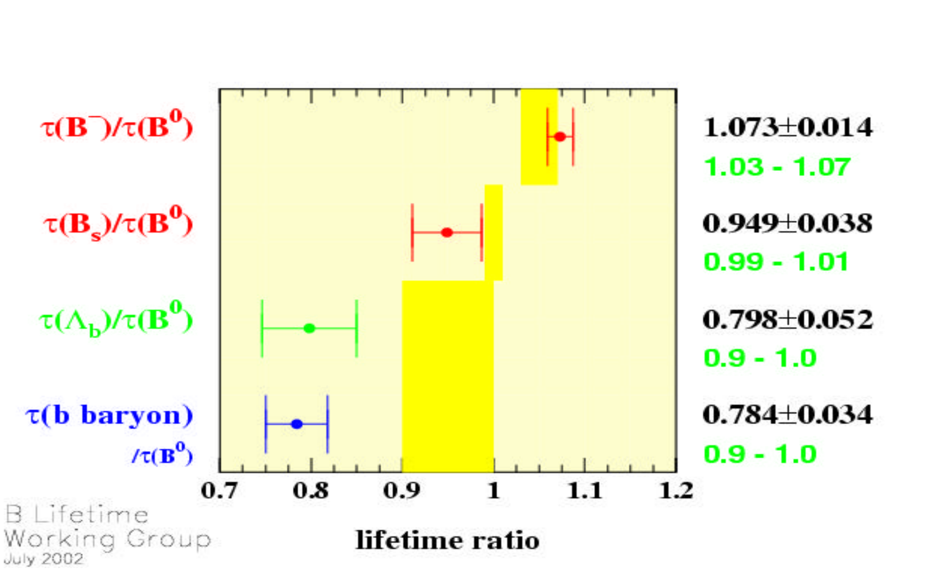
PDG values

B hadron	Lifetime (ps)	cτ (μm)
B^+	1.674 +/- 0.018	502
B^0	1.542 +/- 0.016	462
B_s	1.461 +/- 0.057	438
B_c	0.460 +/- 0.180	138
Λ_b	1.229 +/- 0.080	368

- *Test of Heavy Quark Expansion* predictions of the lifetimes for different B hadron species:

$\tau(B^+) > \tau(B^0) \sim \tau(B_s) > \tau(\Lambda_b) >> \tau(B_c)$

- CDF can be competitive in *all B hadron lifetimes* measurements (better momentum and vertex resolution than any other current experiment)
- B^0 and B^+ can be used as control samples



B hadron Lifetimes in exclusive decays

J/y trigger

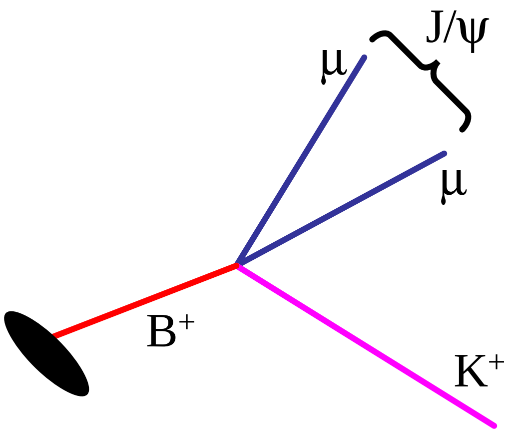
- **Clean**
- **Fully reconstructed**
- **Lifetime unbiased**
- **"Low statistics"**

B^+ ® J/y K^+
® J/y K^{*+}

B^0 ® J/y K^{0*}
® J/y K_s

L$_b$ ® **J/y** L$_c$

B^0_s ® **J/y** f



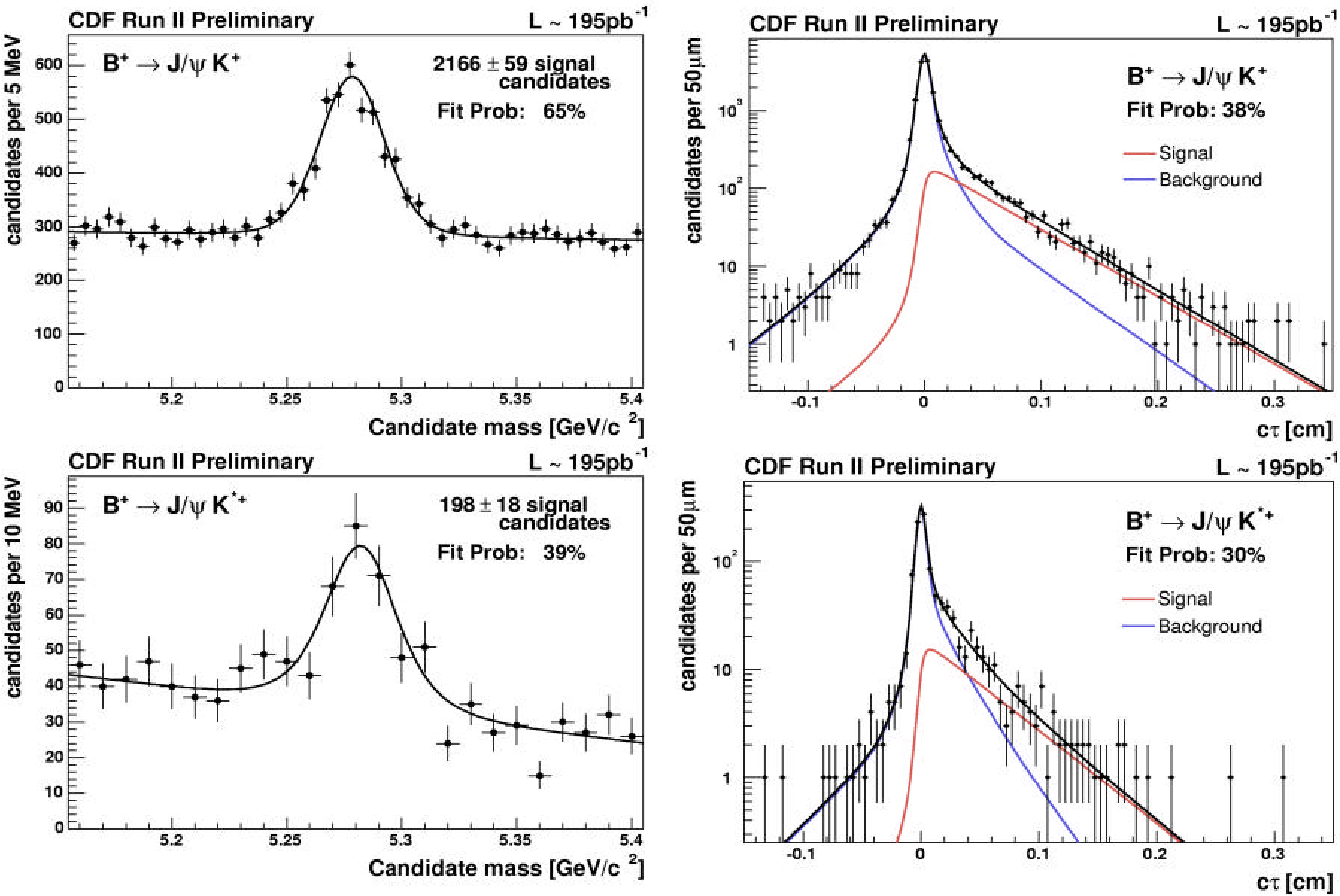
Lifetime measurement:

- Reconstruct decay length
- Measure p_T of decay products

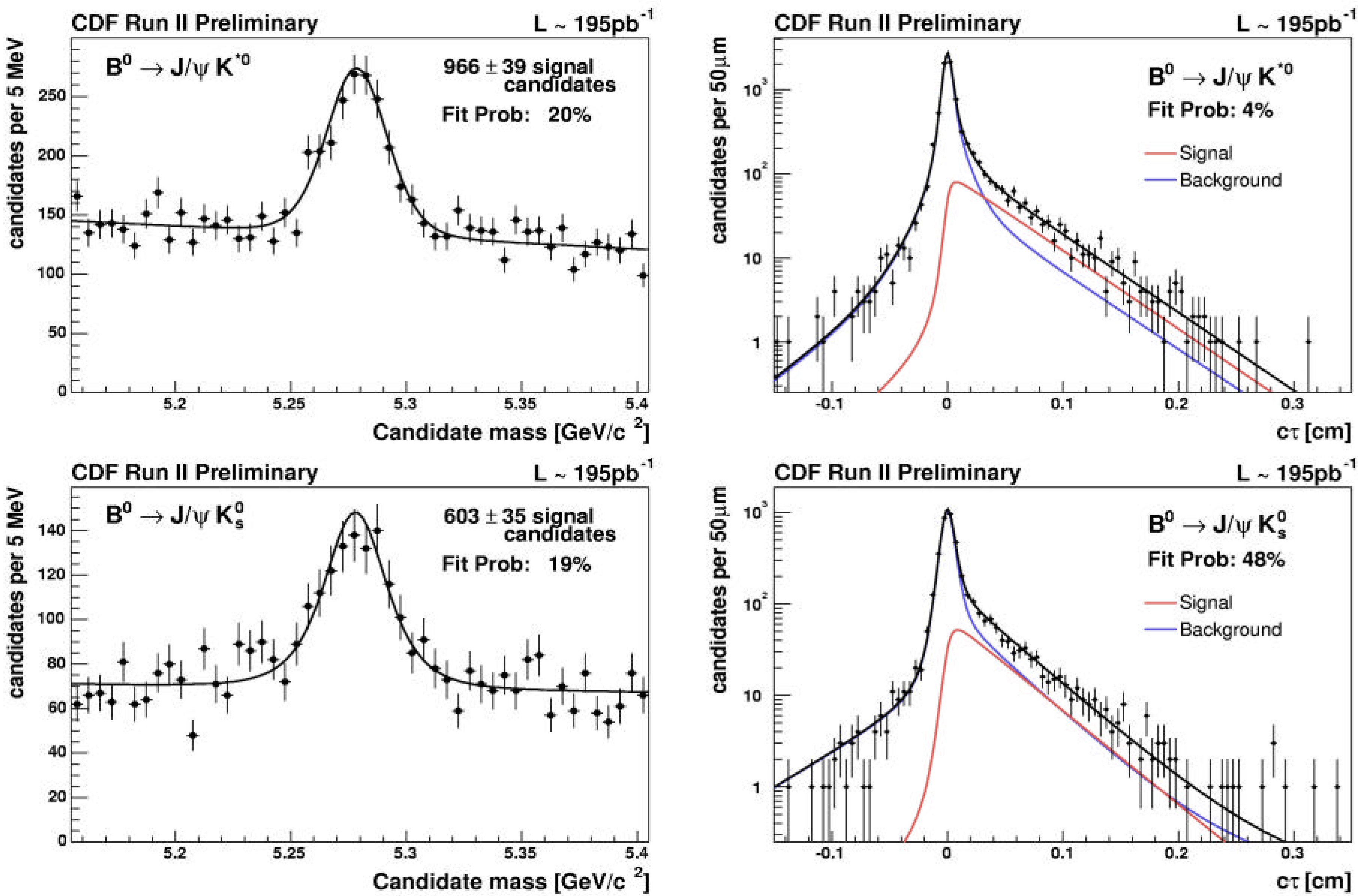
$$ct = \frac{L_{xy}}{b\ g} = \frac{L_{xy}\ m(B)}{P_T(B)}$$

Exclusive $B^+ \to J/\psi X$ Lifetimes

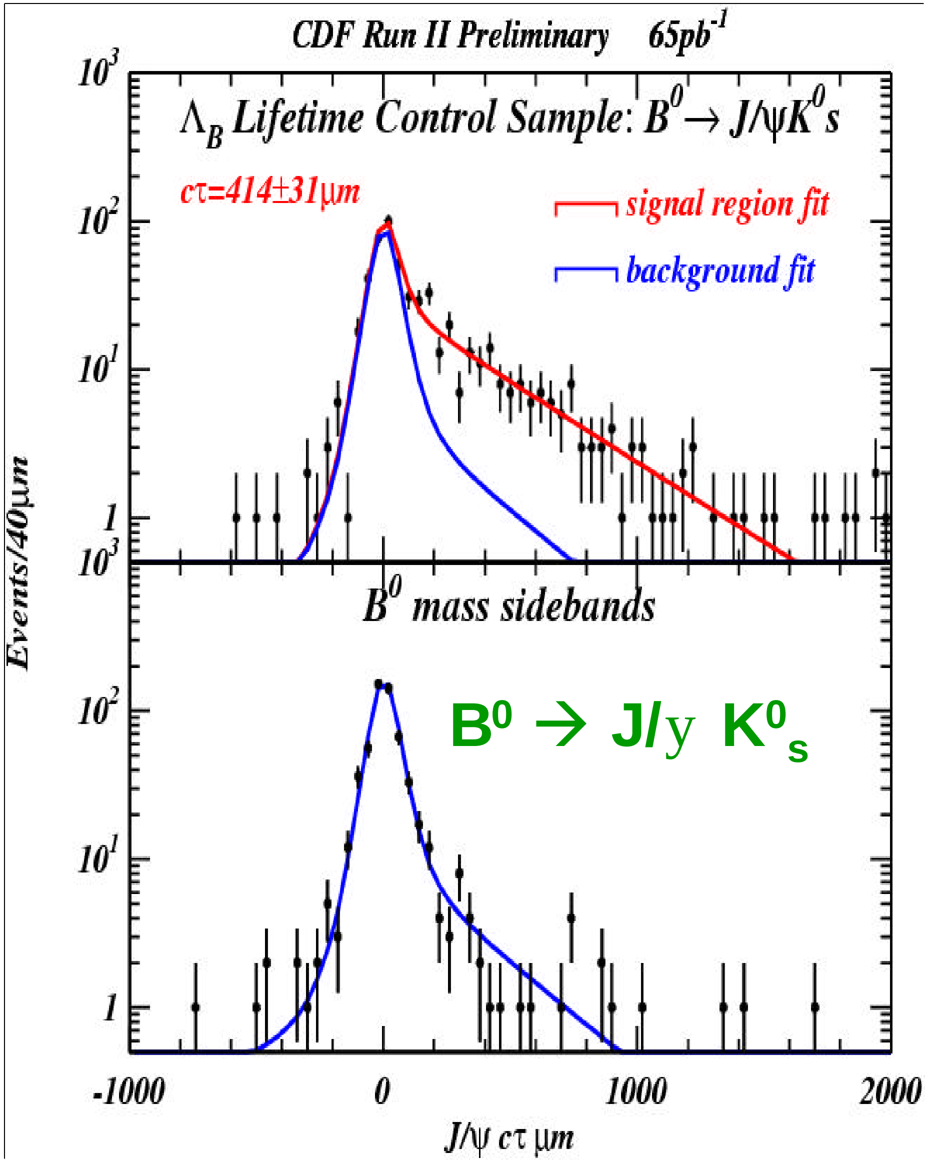
Simultaneous fit of Mass and $c\tau$ distributions

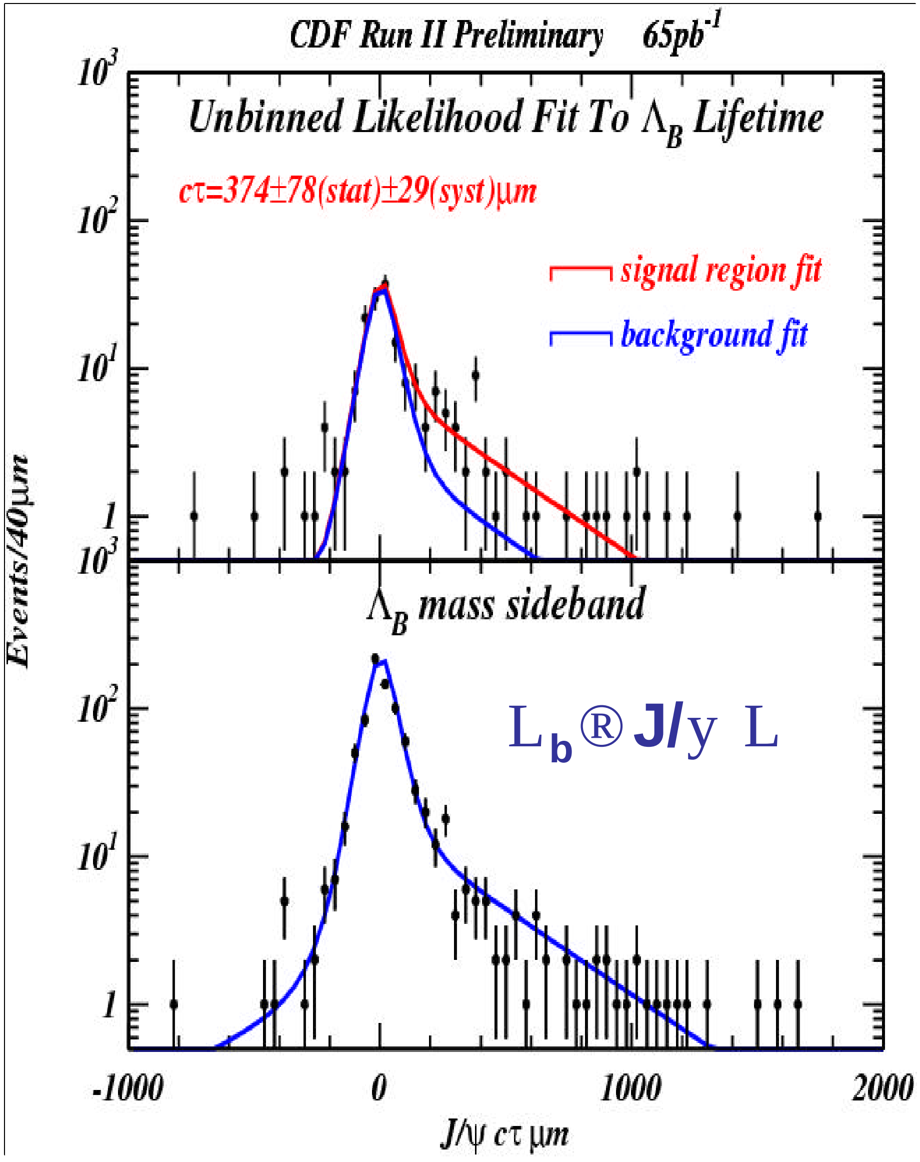


Exclusive $B^0 \to J/\psi X$ Lifetimes

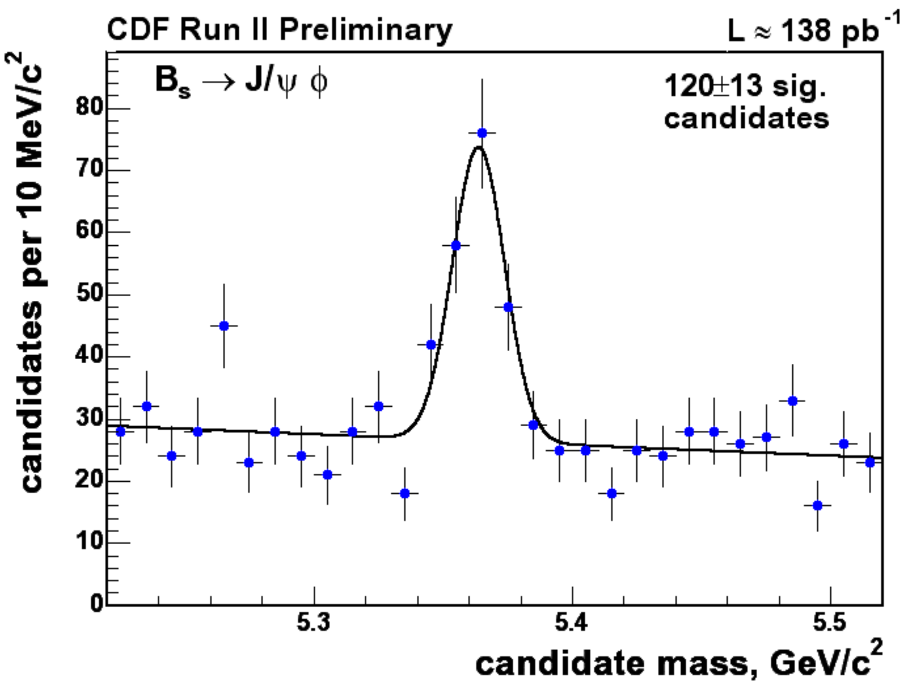


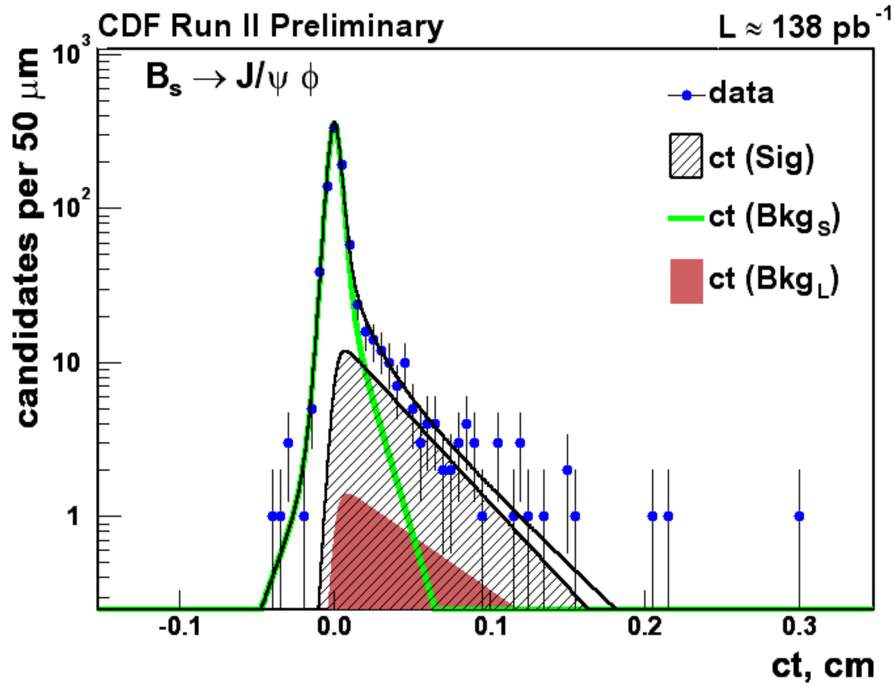
$\Lambda_b \rightarrow J/\psi\ \Lambda$ Lifetime





Exclusive $B_s \to J/\psi\phi$ Lifetimes





CDF Run I I preliminary results (in ps)

B hadron	CDF measurement	PDG value
B^+	1.66 +/- 0.04 +/- 0.02	1.674 +/- 0.018
B^0	1.49 +/- 0.05 +/- 0.03	1.542 +/- 0.016
Λ_b	1.25 +/- 0.26 +/- 0.10	1.229 +/- 0.080
B_s	1.33 +/- 0.14 +/- 0.02	1.461 +/- 0.057

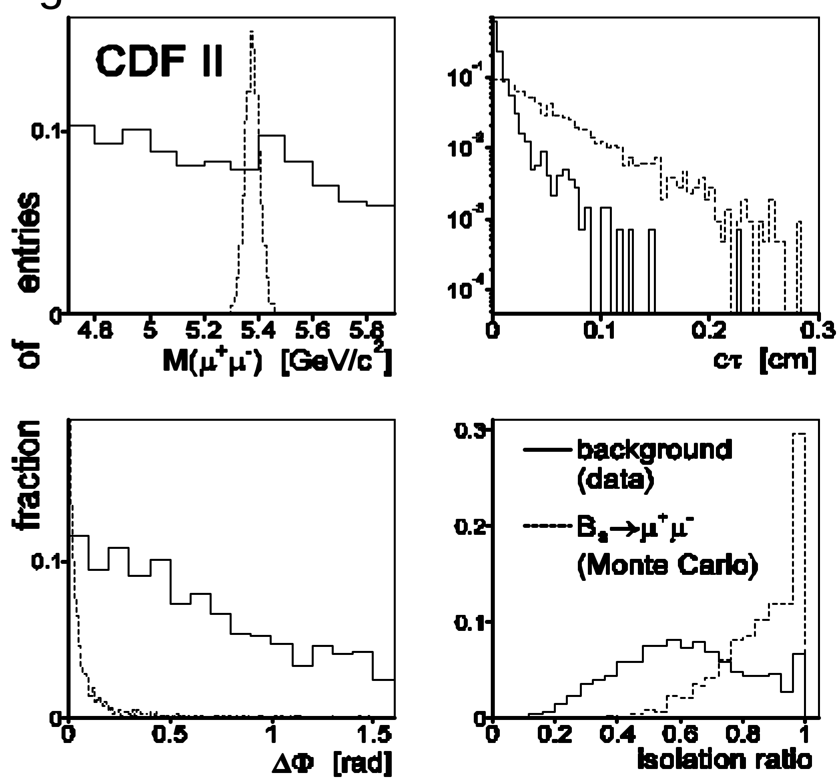
$R(B^+/B^0)$ = 1.119 +/- 0.046 (stat.) +/- 0.014 (syst.)

(PDG: 1.073 +/- 0.014)

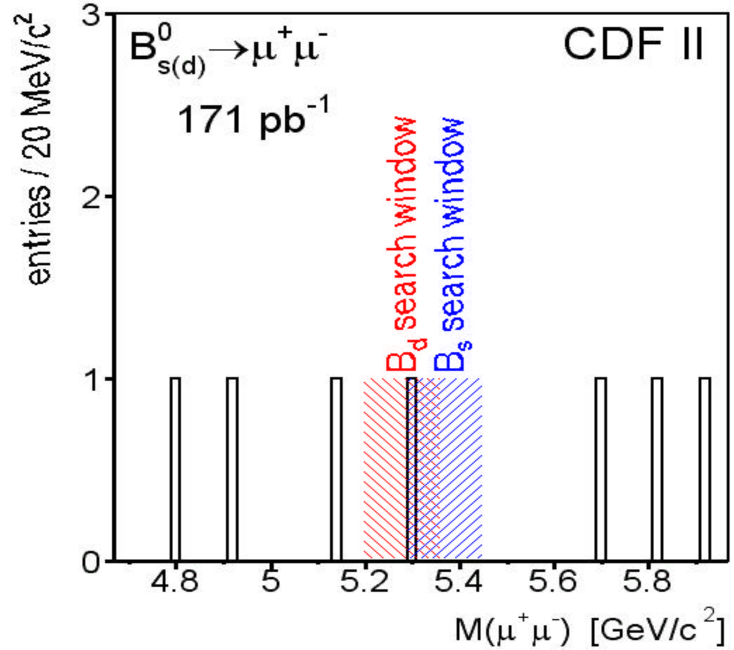
Rare B decays: B $_{s(d)} \rightarrow \mu^+\mu^-$

- SM prediction: $BR(B_s \rightarrow \mu^+\mu^-) = (3.8 \pm 1.0)\ 10^{-9}$
- Several extensions to the SM predict an enhancement of this branching ratio by 1 to 3 orders of magnitude
- If there is not excess we can already constrain several SUSY models!

Discriminating variables



"Blind" analysis: cuts were optimized before looking at the signal mass region

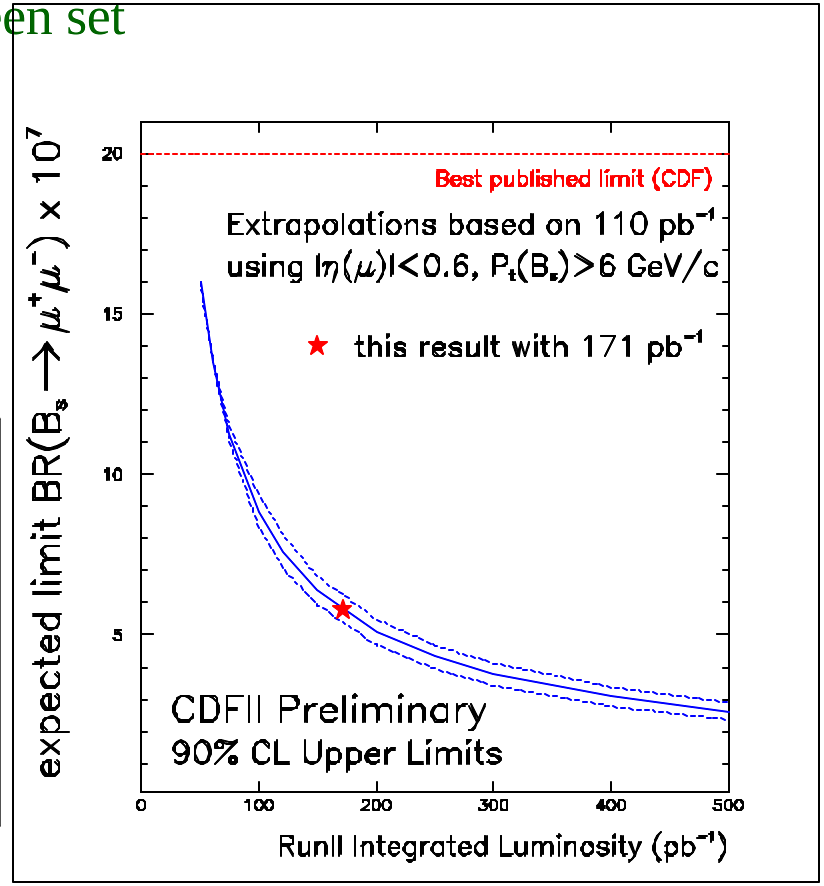


Final mass distribution

Rare B decays: $B_{s(d)} \rightarrow \mu^+\mu^-$

- No excess has been found unfortunately
- Limits on the Branching fractions have been set

(Expected/Observed) **BR limits vs. luminosity**



Already Submitted to PRL!

	$B_s \rightarrow \mu^+\mu^-$	$B_d \rightarrow \mu^+\mu^-$
Background	1.05 +/- 0.30	1.07 +/- 0.31
Data	1	1
BR limit @95% C.L.	7.5×10^{-7}	1.9×10^{-7}
BR limit @90% C.L.	5.8×10^{-7}	1.5×10^{-7}

Best world result

Slighly better results than Belle and BaBar

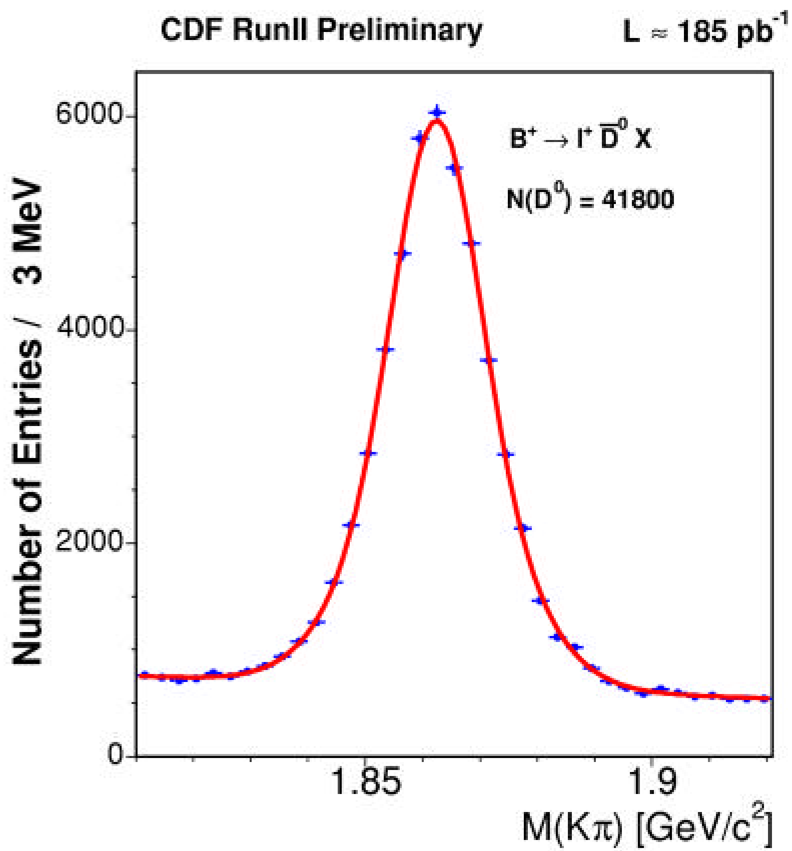
1.6×10^{-7}

2.0×10^{-7}

Semileptonic B samples

lepton + displaced vertex track trigger collects a lot of Semileptonic B decays!

- **It provides:**
  - **High statistics**
  - **“Clean” environment**
  - **Good control sample**
- **But:**
  - **Lifetime bias**
  - **Sample composition B^0 Û B^+**



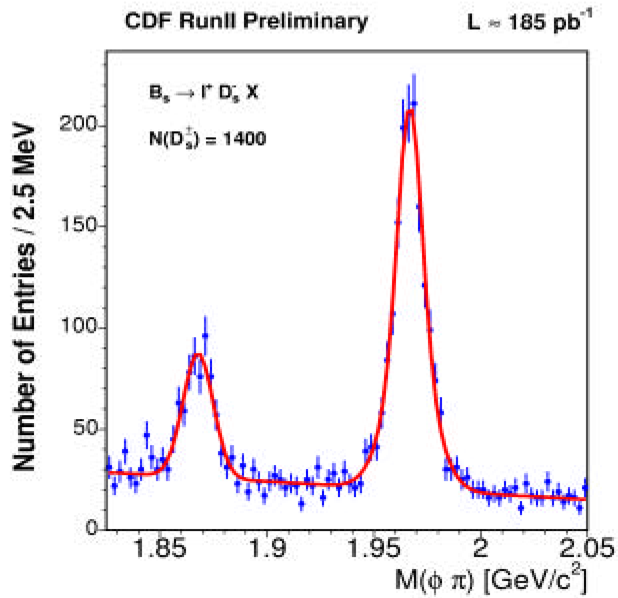
- Work in progress:
  - Understand lifetime measurements in this sample
  - $B_{s(d)}$ mixing might be done in Semileptonic B decays

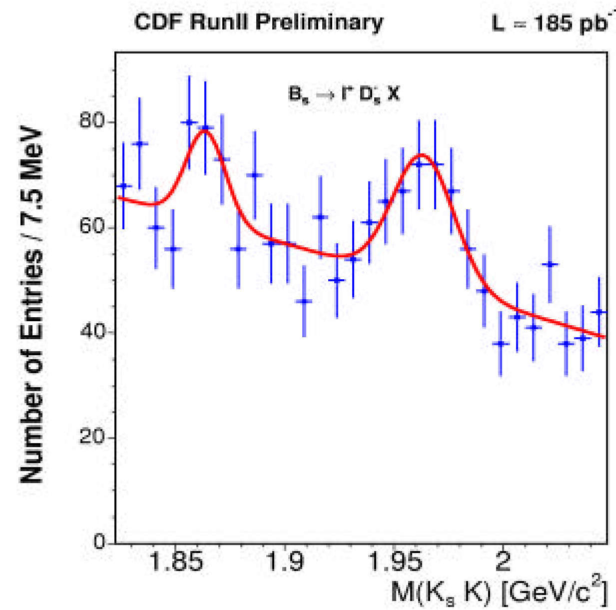
> 40000 B → l D^0 X decays!

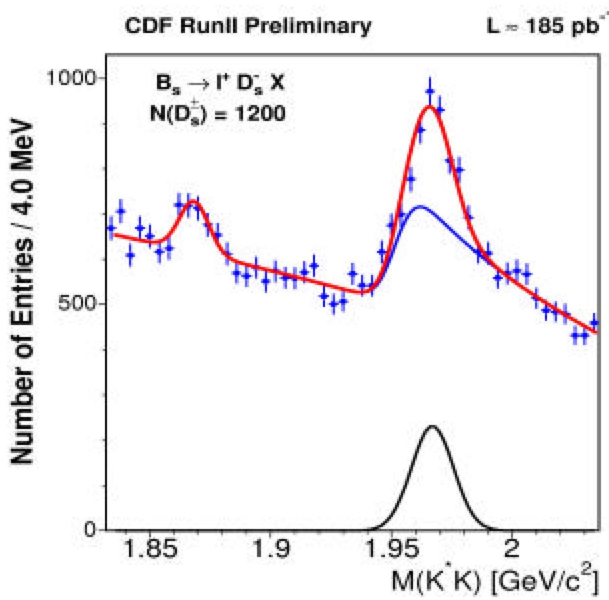
Semileptonic B_s samples

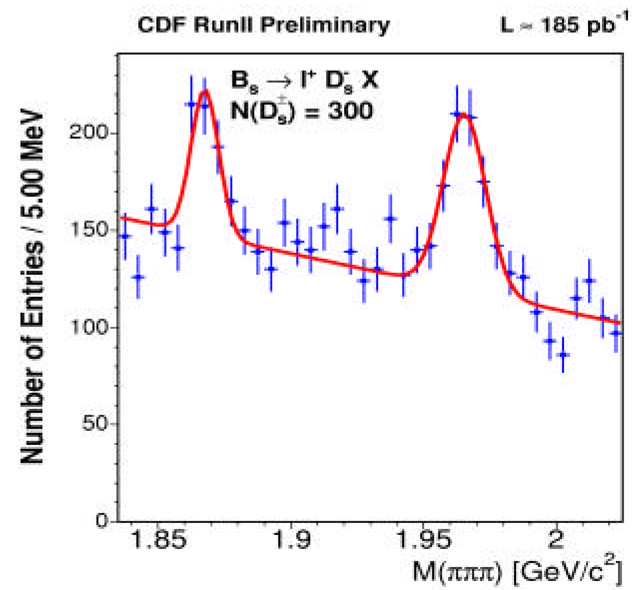
$B_s \rightarrow l\, D_s\, X$

Semileptonic B_s decays









Only yields and mass plots today

CP Asymmetries and Decay Rate ratios

- The huge amount data collected by the Two Track Trigger have been used for this analysis

Relative branching ratios:

$\Gamma(D^0 \to K^+K^-) / \Gamma(D^0 \to K\pi)$

$\Gamma(D^0 \to \pi^+\pi^-) / \Gamma(D^0 \to K\pi)$

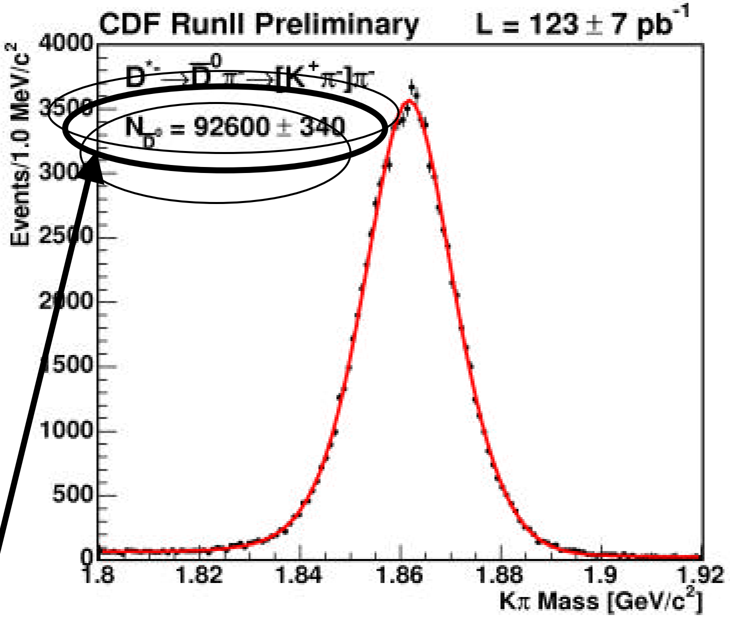
$\Gamma(D^0 \to KK) / \Gamma(D^0 \to \pi\pi) \sim 2.8$ (SM)

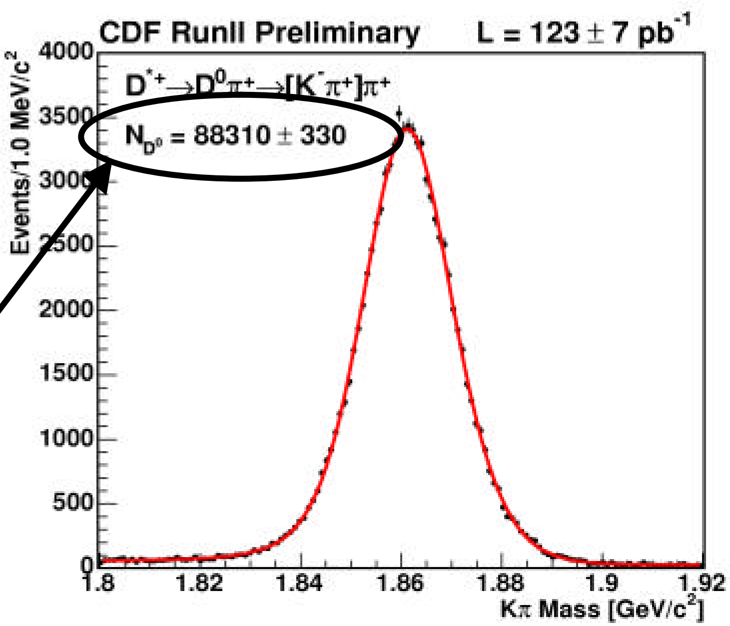
Direct CP-violating decay rate assymetries:

$$A_{CP} = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to f)} \approx 0(SM)$$

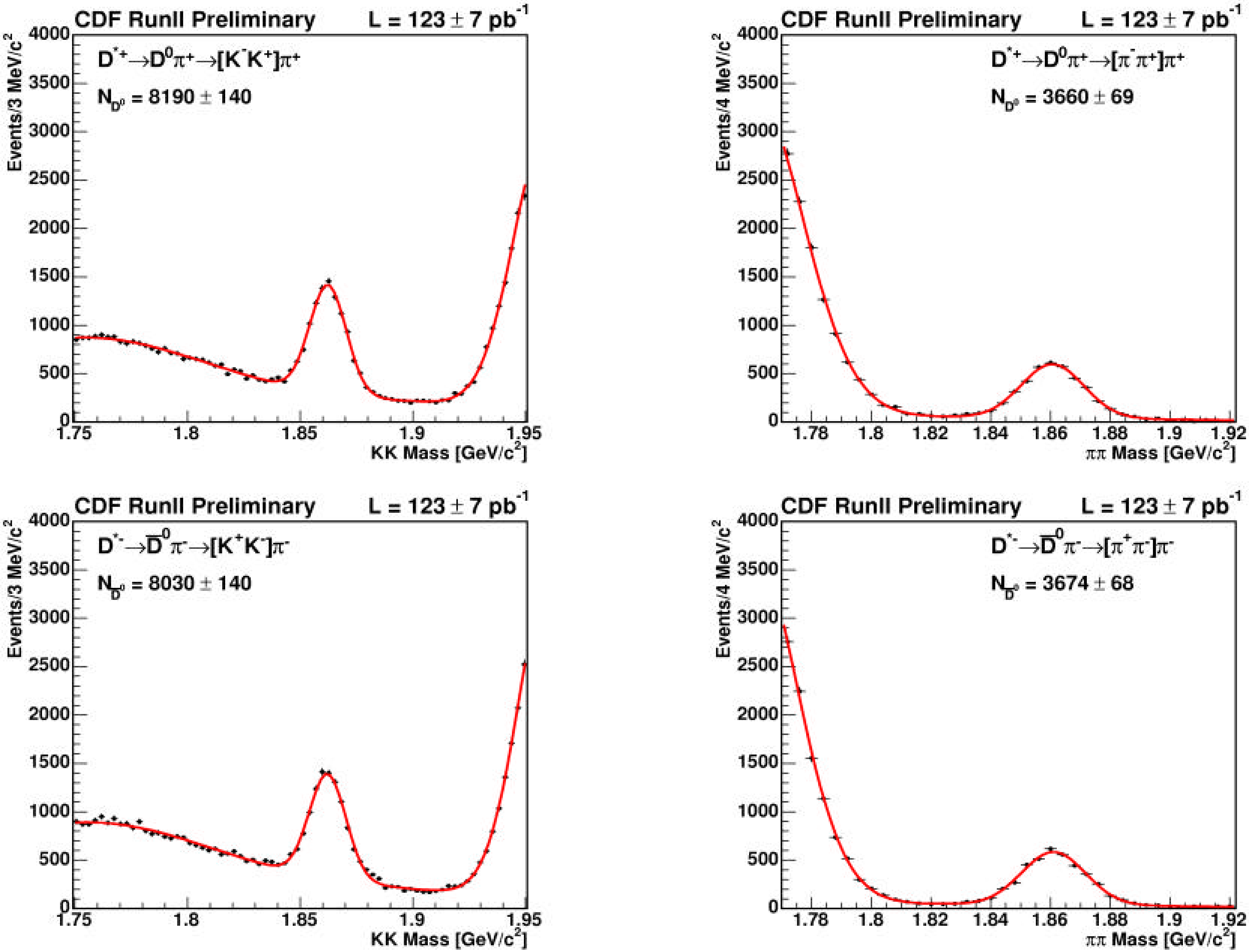
- Candidates selected as: $D^{*+/-} \to D^0 \pi$ (unbiased tag of the D^0 flavor)

~2 X 90000 $D^{*+/-}$!!!



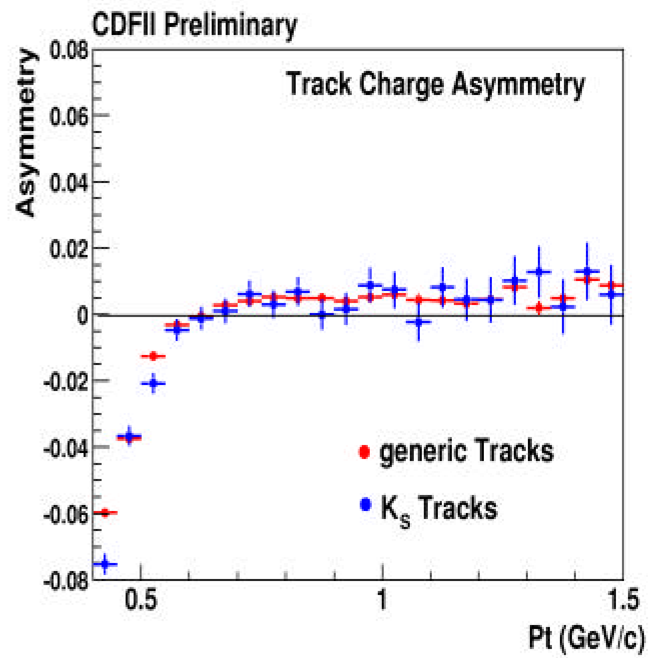


CP Asymmetries and Decay Rate ratios



CP Asymmetries and Decay Rate ratios

Very important to understand the asymmetry of the CDF detector!!!



Results are computed after applying a correction for the intrinsic charge asymmetry of the detector response and tracking algorithms

Ratio	CDF	FOCUS
$\Gamma(D^0 \to KK)/\Gamma(D^0 \to K\pi)$	(9.96 +/- 0.11 +/- 0.12)%	(9.93 +/- 0.14 +/- 0.14)%
$\Gamma(D^0 \to \pi\pi)/\Gamma(D^0 \to K\pi)$	(3.608 +/- 0.054 +/- 0.040)%	(3.53 +/- 0.12 +/- 0.06)%
$\Gamma(D^0 \to KK)/\Gamma(D^0 \to \pi\pi)$	(2.762 +/- 0.040 +/- 0.034)%	(2.81 +/- 0.10 +/- 0.06)%

$A(D^0 \to KK)$ = (2.0 +/- 1.2 (stat.) +/- 0.6 (syst.))%
$A(D0 \to \pi\pi)$ = (1.0 +/- 1.3 (stat.) +/- 0.6 (syst.))%

CLEO-II

$A(D^0 \to KK)$ = (0.0 +/- 2.2 (stat.) +/- 0.8 (syst.))%
$A(D0 \to \pi\pi)$ = (1.9 +/- 3.2 (stat.) +/- 0.8 (syst.))%

Pentaquarks searches

- The beginning: Announcements from several experiments around the world provide evidence for the existence of an exotic baryon, a *Pentaquark* with strangeness S=+1

- What are Pentaquarks?
    - Minimum content: 4 quarks and 1 antiquark $\left(q_1 q_2 q_3 q_4 \overline{Q}\right)$
    - "Exotic" Pentaquarks if the antiquark has a different flavor than the other 4 quarks
    - Quantum numbers can not be defined by 3 quarks alone

Summary of experiments

Θ^+, M ~ 1.53 GeV/c2, Γ <~ 15 Mev/c2)

- LEPS, $\gamma n \to K^- \Theta^+ \to K^- K^+ n$, 4.6 σ, M = 1540 MeV/c^2
- DIANA at ITEP, K^+ Xe $\to \Theta^+ N ? \to K_s p N$, 4.5 σ, M = 1539 MeV/c^2
- CLAS, $\gamma d \to \Theta^+ p K^- \to n K^+ p K^-$, 5.3 σ, M = 1542 MeV/c^2
- SAPHIR, $\gamma p \to K_s\ \Theta^+$, 4.8 σ, M = 1540 MeV/c^2
- ν's WA21, E180… $\Theta^+ \to K_s p$ spectrum, 6.7 σ, M = 1533 MeV/c^2
- CLAS, $\gamma p \to p^+ \Theta^+ K^- \to$ **p** $^+ K^+ n K^-$, 7.8 σ, M = 1555 MeV/c^2
- HERMES, $\gamma n \to K\ \Theta^+ \to K^- K^+ n$, 5 σ, M = 1527 MeV/c^2
- ZEUS, ep $\to \Theta^+ X \to K_s p X$, 5 σ, M = 1525 MeV/c^2

Are they Pentaquarks ?

$\Xi_{3/2}$:{Ξ^0, Ξ^-, Ξ^{--}}, M ~ 1862 MeV/c^2

- NA49 at SPS/CERN (pp collider at Ecm = 17.2 GeV)

$$\Xi_{3/2}^{+/--} \to \Xi^{+/-} p^{+/-}, \Xi^{+/-} \to \Lambda p^{+/-}$$

Today!

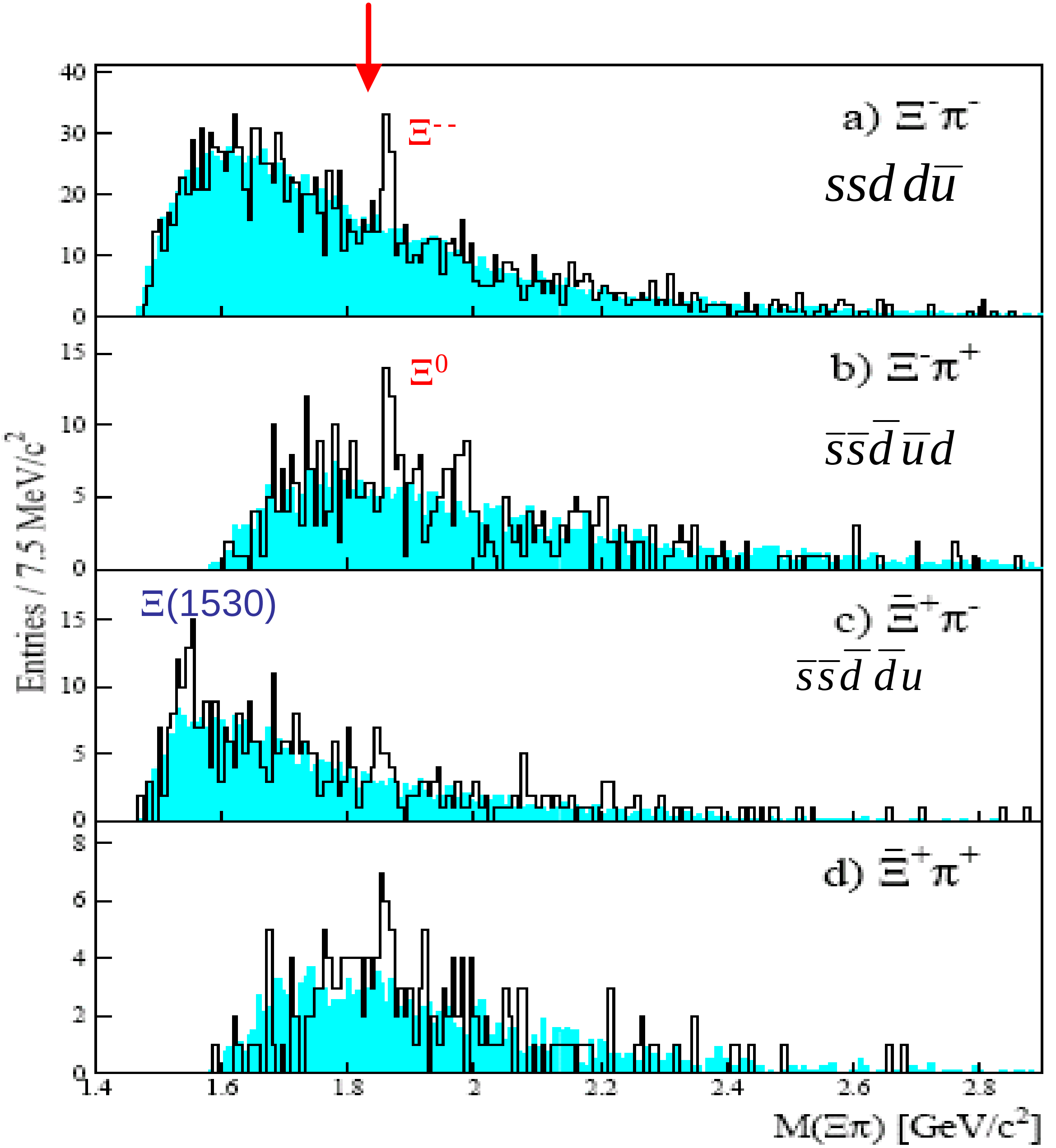
Last week!: New state $\to$ D^{*-} p

- H1, ep $\to D^{*-}$ p X, M = 3099 MeV/c^2

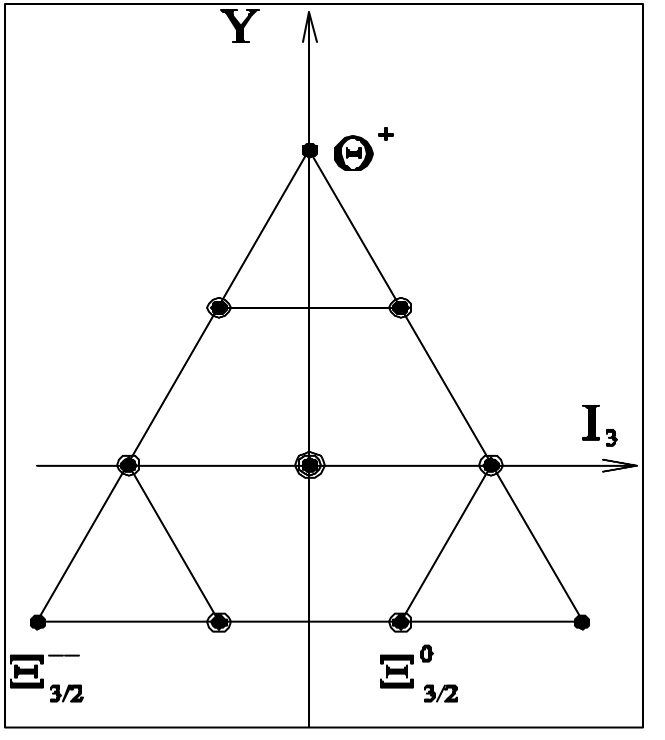
BUT:

- **all results are obtained with relatively low statistics, 20-100 events in peaks, S/B~1-0.3, S/sqrt(S+B)~3-6**
- **some other experiments are seeing "nothing" in similar searches (BES, Hera-B this week…)**

The new cousin of Θ^+: Ξ^{--}



M=1.862± 0.002 GeV

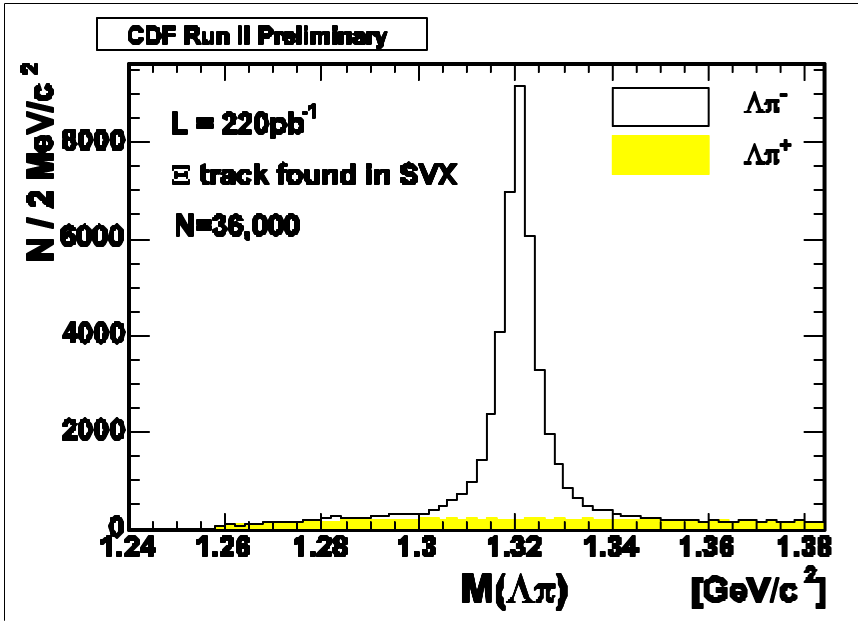


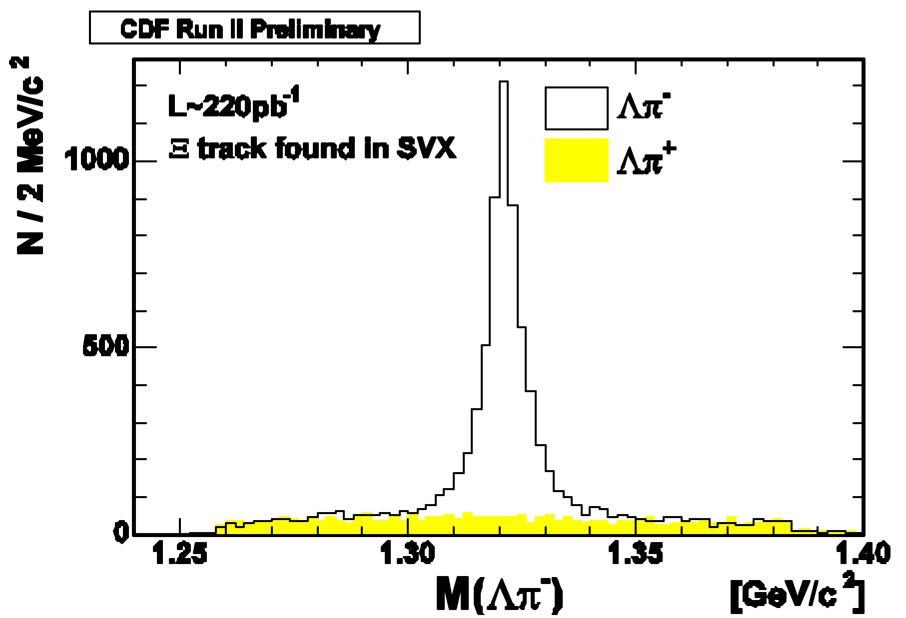
NA49 CERN SPS hep-ex/0310014

Pentaquarks searches

• CDF has developed tracking of long lived hyperons (Ξ and Ω) in the SVX detector

• Silicon tracking of hyperons improves momentum and impact parameter resolution as well as background reduction





Two Track Trigger

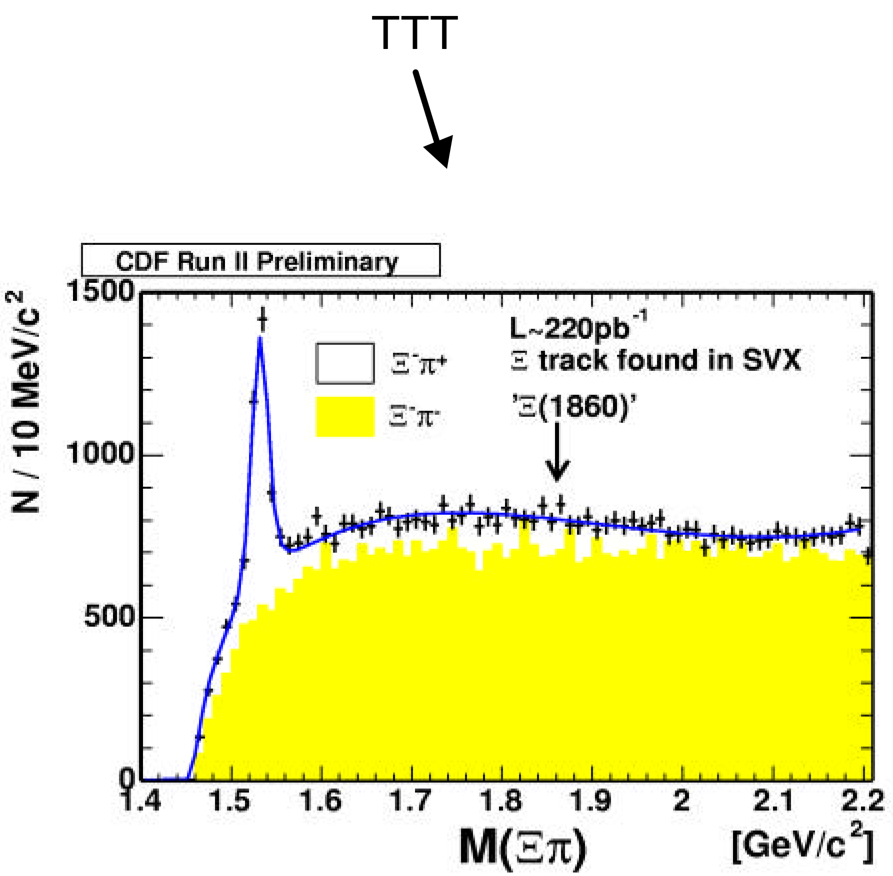
Jet 20 Trigger

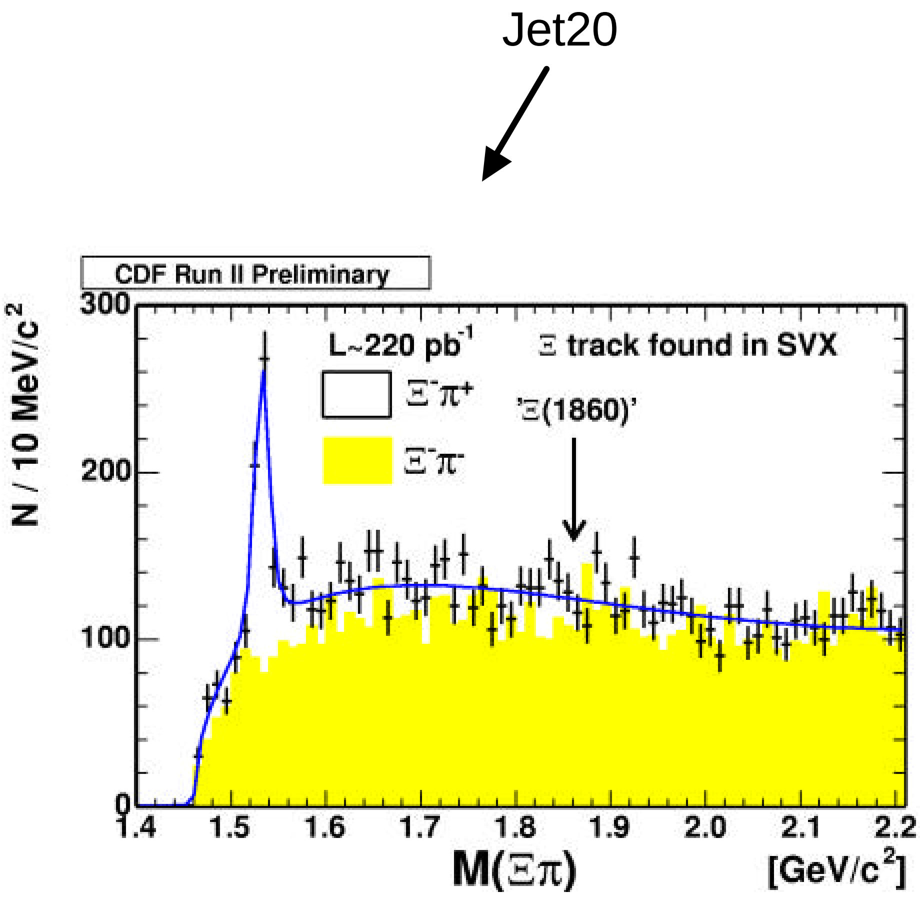
Analysis has been performed using two different triggers

N_{TTT} ~ 18 times larger than NA49 data
N_{Jet20} ~ 2 times larger than NA49 data

Pentaquarks searches

But… **No excess is observed in the CDF data**





Pentaquarks searches

- No signals have been found
- Upper limits have been set
- Results confirmed using two different triggers

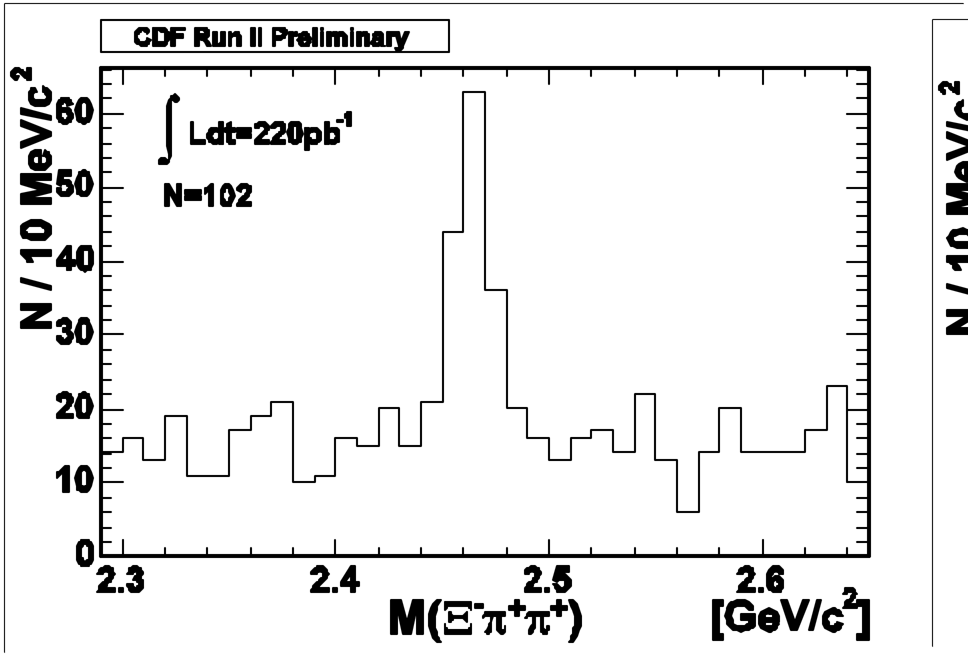
Channel (TTT)	**# of events**	**R(X_{1860}/X_{1530}) U. L. 95% C.L.**	**R(X_{1860}/X_{1530}) NA49**
$X^{-}p^{+}$	**57+/-51**	**0.07**	**~0.21**
$X^{-}p^{-}$	**-54+/-47**	**0.04**	**~0.24**
$X^{-}p^{+/-}$	**47+/-70**	**0.08**	**~0.45**

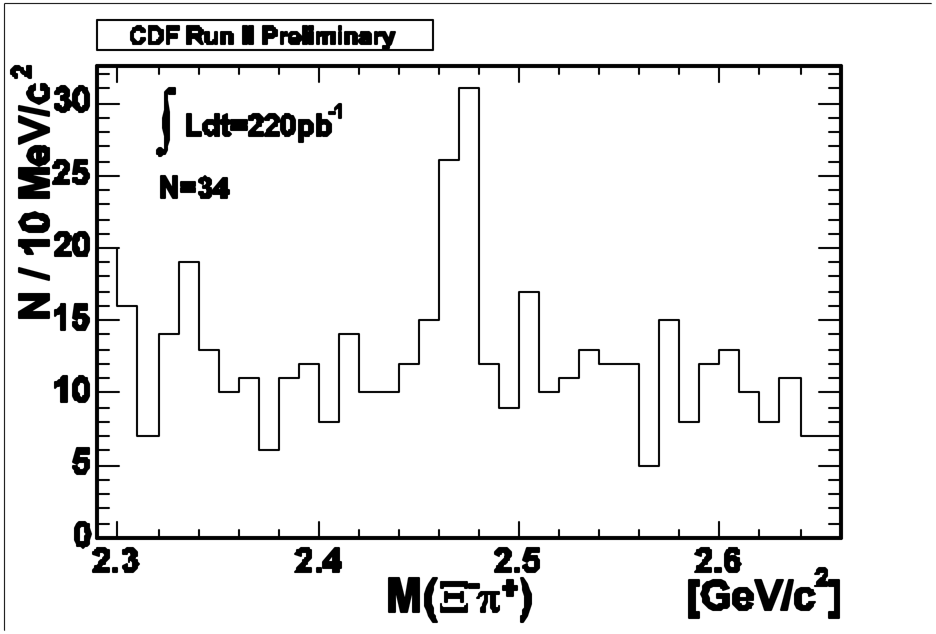
Other Pentaquarks searches are in progress at CDF, to be continued…

Charmed-strange baryons

$\Xi_c^+ \rightarrow \Xi^- p^+ p^+, \Xi^- \rightarrow \Lambda p^-$

$\Xi_c^0 \rightarrow \Xi^- p^+, \Xi^- \rightarrow \Lambda p^-$





This is the first observation of charmed-strange isodoublet $\{\Xi^0_c, \Xi^+_c\}$ in hadron collider

Charm/Bottom summary

- **Measured Hadron B lifetimes using fully reconstructed modes: precision at the level of 3% for B^0 and B^+ hadrons**
- **Limits on BR($B_{s(d)} \to$ mm)) of the order of 10^{-7}: best world limits**
- **Large Semileptonic B sample collected by the lepton + Displaced Track Trigger**
- **Studies on CP Asymmetries and Decay Rate Ratios of Cabibbo supressed D^0 decays**
- **Pentaquarks searches: no excess found yet**

Conclusions

- **Starting an era of QCD precision measurements, Jets with E_t up to 600 GeV**
- **Pythia for Underlying Event well tuned at CDF**
- **World best $B_s \rightarrow$ mm limit, BR($B_s \rightarrow$ mm) < 5.8 X 10^{-7} at 90% C.L.**
- **Precision charm Physics**
  - $A(D^0 \rightarrow KK) = (2.0 +/- 1.2\ (stat.) +/- 0.6\ (syst.))\%$
  - $A(D0 \rightarrow \pi\pi) = (1.0 +/- 1.3\ (stat.) +/- 0.6\ (syst.))\%$
- **We can not confirm $X_{2/3}^{--}$ from NA49**

(hard) work in progress, stay tuned!